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Edited for the Council by Capt. J. LAURENCE PRITCHARD, Hon. Fellow

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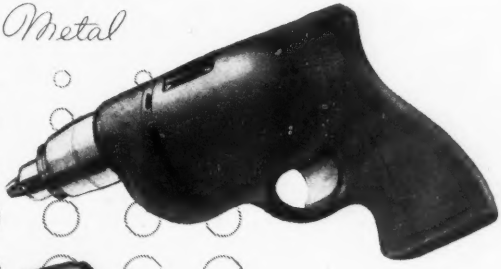

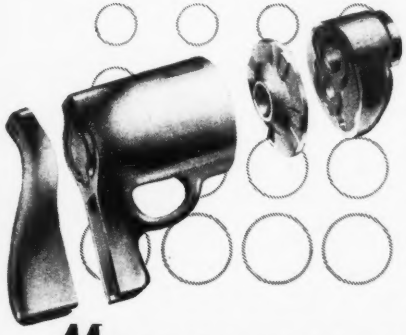

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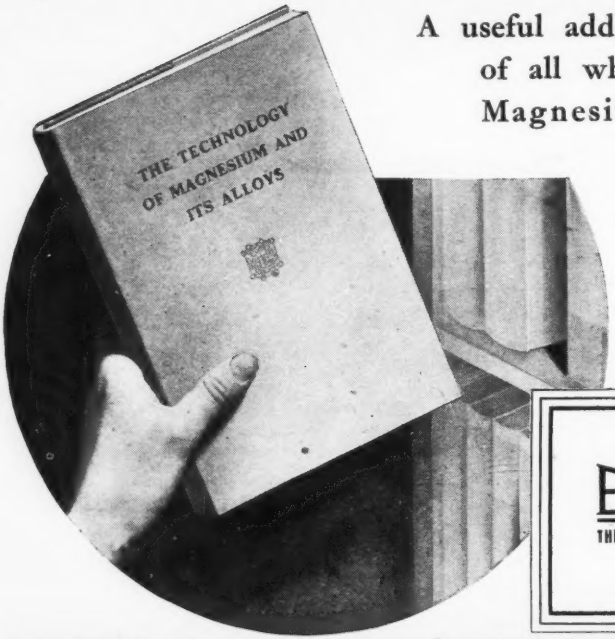

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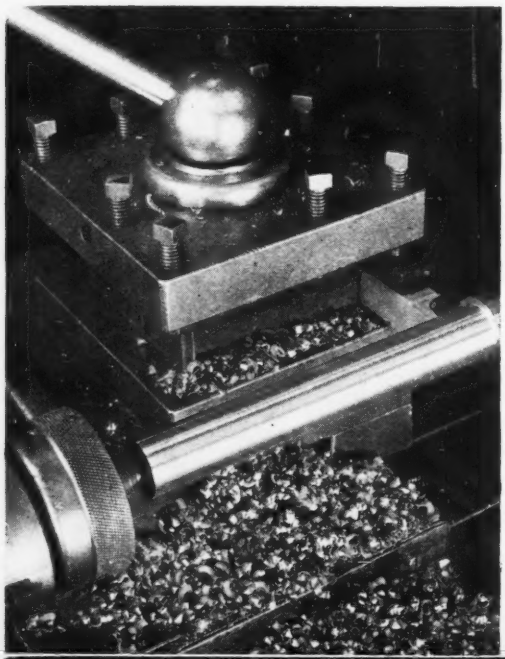

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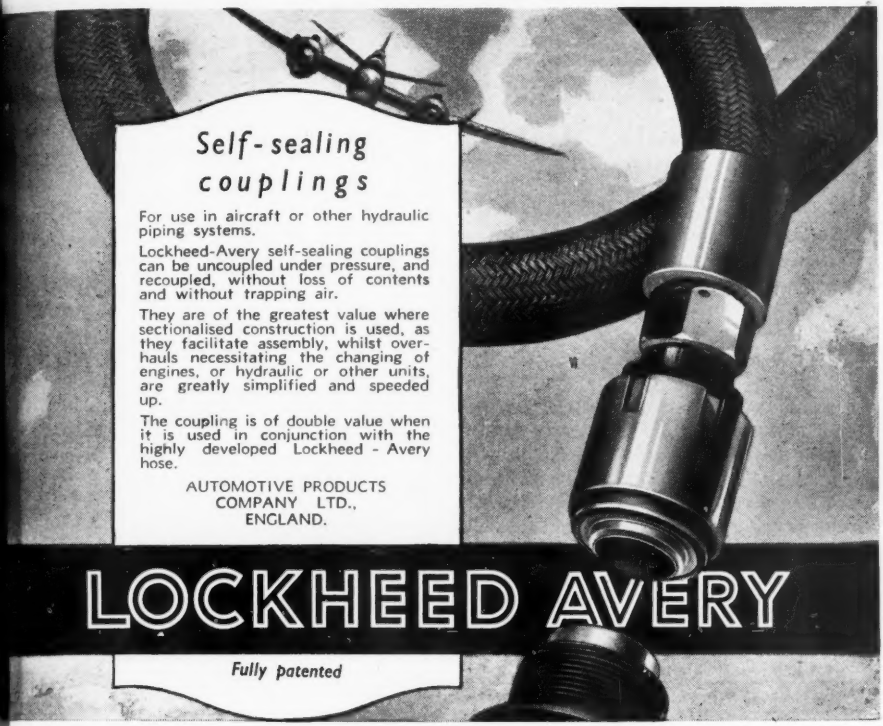

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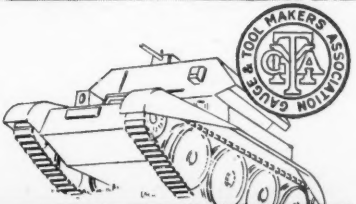

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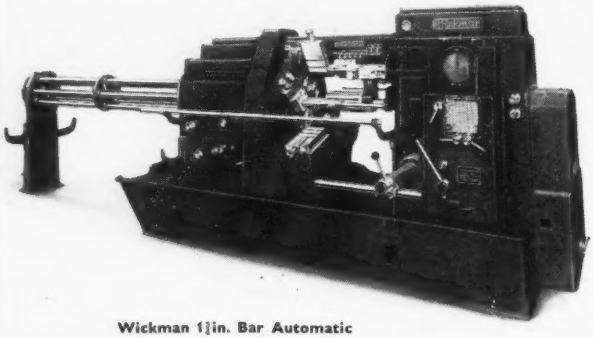

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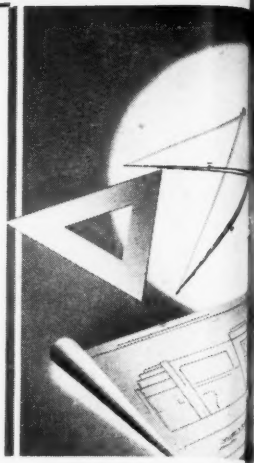

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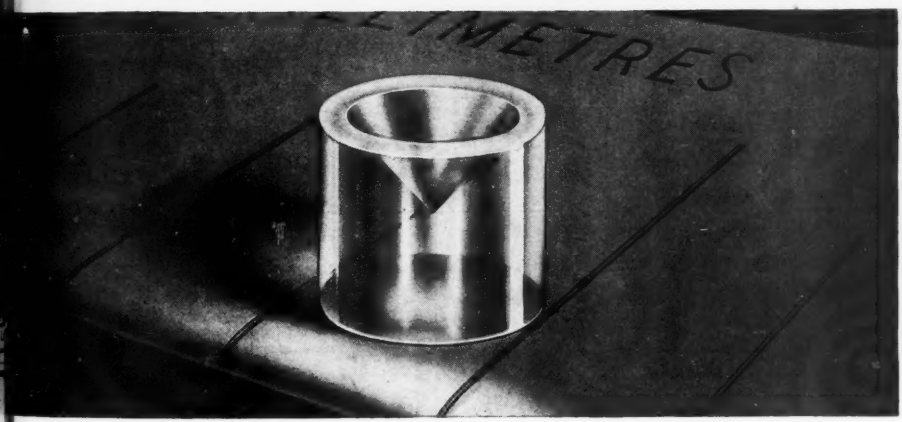

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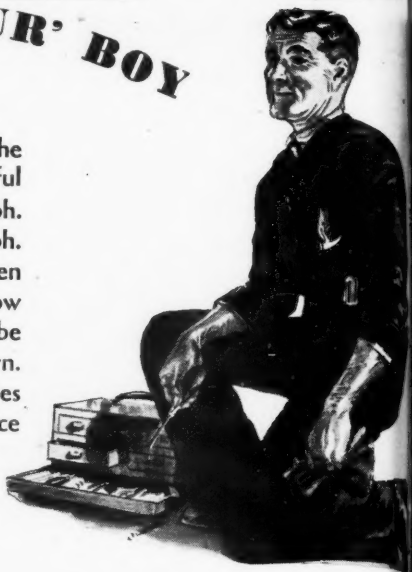

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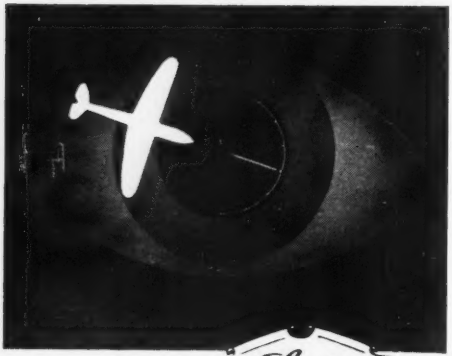

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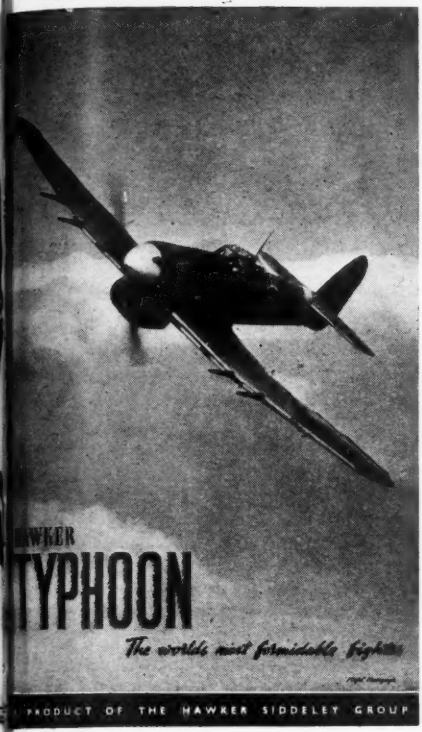

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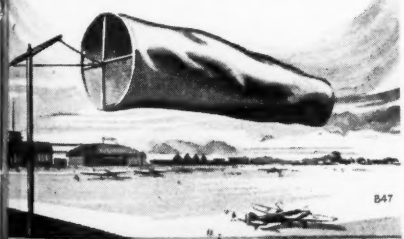

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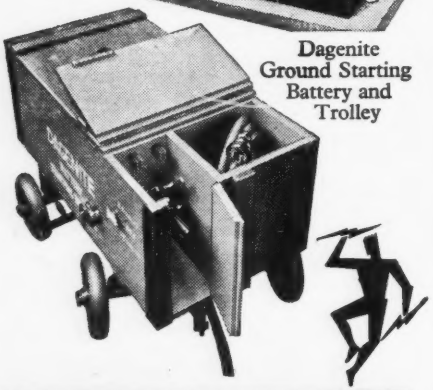

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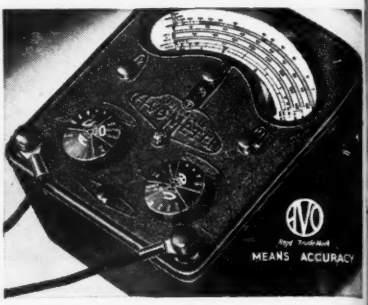

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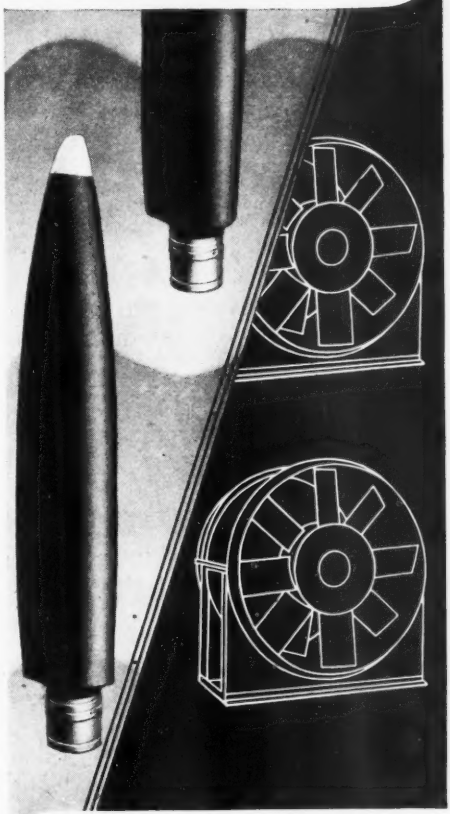

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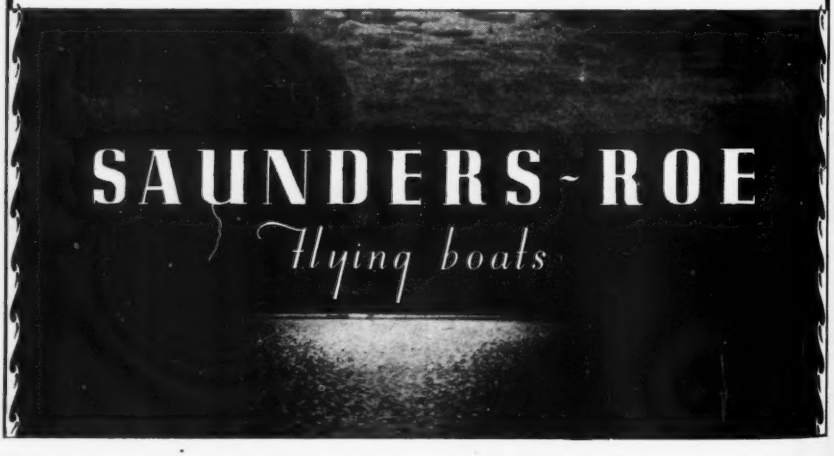

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SEPTEMBER, 1944.

Associate Fellowship Examination, December, 1944.

Entries for the December, 1944, Associate Fellowship Examination must be received by the Secretary by September 30th, 1944.

1944 Journals.

The Secretary would very much appreciate it if those members who have finished with their Journals issued January-August, 1944, would return them as the stocks in the Society's possession are very low.

Graduates' and Students' Section.

A Meeting of the Graduates' and Students' Section will be held in the Library of the Society at 4, Hamilton Place, W.1, on Wednesday, September 6th, at 7.30 p.m., when Mr. W. S. Hemp, A.F.R.Ae.S., will lecture on "Some Dynamical Problems in the Design of Large Aircraft"; and on October 4th, at 7.30 p.m., when Squadron-Leader Stewart, R.A.F., will lecture on "Some Physiological Aspects of Flying."

Branch Lectures.

Sir Roy Fedden, M.B.E., F.R.Ae.S., will lecture on "An Historical Review of Aircraft Power Plant with Reference to American War-Time Production" to the following Branches:—

Derby Branch—6.30 p.m. on Monday, September 4th, 1944.

Luton Branch—7.15 p.m. on Wednesday, September 13th, 1944.

Acknowledgments.

The Council acknowledge with thanks the gifts of Journals from the following Members:—

Sir Francis Shelmerdine, Fellow; Major B. W. Shilson, Fellow; Mr. M. H. Volk, Fellow; Mr. Y. Kritchevsky, Companion; Mr. F. V. Holmes, Associate Fellow; Mr. D. V. Wordsworth, Graduate; Mr. W. Davidson, Associate Fellow.

Election of Members.

The following members were recently elected:—

Associate Fellows.—Vivian Richardson Billings, Mark Fisher, Peter William Gooch, William Isbister (from Graduate), Joe Ravenscroft Leach, Rene Lucien, Arthur John Luckett, Sidney Arthur Macey, Gordon James Malin, John Burne Mills (from Graduate), Henry Nattrass, Harold George Parker, Robert Rodger (from Student), Arthur Godfrey Shove (from Student), Stewart S. Tresilian, Robert Herbert Whitby (from Student), Melville Thomas Woodcock, Joseph Wright.

Associates.—Charles Ferdinand Andrews, Ronald Merriman Barry (from Companion), John Milton Berry, Joseph Capel, Edgar Grafton Carlisle, Francis Insley Chambers, George Arthur Coombes, Francis James Day, Arthur Kitching Ellison, Alan Lewis Fermor, Edward Randolph Godlieb, Reginald Hallas, John Hands, Richard William Holmes, Isaac Alfred Howard, George Percy Jewell (from Graduate), Eric Horace Marson, Denis Charles Minett, Charles William Morton, William Charles Pakenham Nicholas, Francis Leo O'Shaughnessy, William Shippen Phillips, Duncan Geoffrey Pitt, Hubert Lewellen Pitt, Sydney Sarjeant, Charles Edward Squires, James Thomson, Gordon Thomas White (from Student).

Graduates.—Edgar Parsons Bridgland (from Student), Thomas Day Griffin (from Student), Robert William Howes, Cyril Arthur Johnson, James Richard Palmer, David Sadler (from Student), Frank William Singleton.

Companions.—Thomas Geoffrey Daish, Maurice Walter Perryman, Ronald Bain Sturrock.

Students.—David Frederick Allen, Frederick Daniel, Leonard William Eyles, Geoffrey Bransom Griffiths, John Flint Griffiths, George Ian Livingston Gunn, Douglas Percival Hart, John Arthur Howard, Harry McPherson Johnston, Roy Edward Lambert, William Frederick Leadbeater, Gordon Frederick Parkinson, John Shields, George Albert Turner, William Albert Webb, Norman Peter White, Peter Gillingham Williams.

Additions to Library: August, 1944.

Pamphlets in italics with location reference following in brackets.
Books marked * or ** may not be taken out on loan.

BB.b.110.—*Aircraft Construction. (Reprint of paper read by H. G. Parker before the Belfast Association of Engineers, Feb. 5th,* 1941.) (PBB.1.a.8.)

BB.d.35.—*Rotol Accessory Drive Equipment.* (*Publication* R.26.) *Rotol, Ltd.,* 1944. (PBB.3.b.7.)

EE.b.80.—*Wright Cyclone 18 in B-29 Super Fortress. Wright Aeronautical Corporation. Press Release,* 16.6.44. (Y.7.d.W.)

EE.b.81.—*New "W" Aluminium Cooling Fan on Wright Cyclone 18. Wright Aeronautical Corporation. Press Release,* 12.7.44. (Y.7.d.W.)

J.g.203.—Weatherwise. John H. Willis. Allen and Unwin, Ltd., 1944. 7/6.

L.k.42.—Principles and Practice of Aviation Medicine. (2nd Ed.) H. G. Armstrong. Baillière, Tindall and Cox, 1944. 36/-.

**R.c.276.—*Account of Aero Exhibition at Allahabad,* 1910. *Lt.-Col. K. L. Laurie. (Handwritten M.S.) (Special Drawer.)*

R.f.96.—Britain in the Air. (Series: "Britain in Pictures.") Wing/Com. Nigel Tangye. William Collins, 1944. 4/6.

S.b.136.—*"The Gnome." (Privately Printed Magazine, issued by the 5th Wing, R.F.C., Moaskar, Egypt, July,* 1916.) (Y.11.iii.a.5.)

*UU.c.—*National Advisory Committee for Aeronautics (U.S.A.): Technical Memoranda No.* 1066. Comparative results of Tests on several different types of Nozzles. M. S. Kisenko. (C.A.H.I. Trans. No. 478. 1940.)

J. Laurence Pritchard, *Secretary and Editor.*

AIRCRAFT POWER PLANT—PAST AND FUTURE

by

SIR A. H. ROY FEDDEN, M.B.E., D.Sc.,
F.R.Ae.S., M.I.Mech.E., M.I.A.E., F.R.S.A., M.S.A.E., M.I.Ae.S.

THE THIRTY-SECOND WILBUR WRIGHT MEMORIAL LECTURE.

The Thirty-second Wilbur Wright Memorial Lecture was delivered before the Society on Thursday, May 25th, 1944, at 6.30 p.m., in the Lecture Hall of the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, by permission of the Council of the Institution. The chair was taken by Mr. A. Gouge, F.R.Ae.S., President of the Society.

The PRESIDENT: This is the thirty-second Wilbur Wright Memorial Lecture. This series of lectures, which have been delivered annually since 1912, through two major wars, is the most important series of lectures in the aeronautical world. Delivered in alternate years by an American and an Englishman it is the turn this year for this country to provide the lecturer. Each year the Council give anxious consideration to the choice of lecturer, not only because of the importance of the lecture, but because in their choice of lecturer they are conferring one of the highest compliments they can to the man chosen.

This year the Council chose for their lecturer Sir Roy Fedden, whose name in aviation as an engine designer is world famous. No one, he felt sure, could speak with greater authority and vision on the probable future developments of aircraft power plants. He was a Past-President of the Society, and it gave him great pleasure to announce that at the Council meeting held this afternoon he had once more been elected as the forthcoming President.

As President he had cabled Orville Wright as follows:—

Orville Wright, Dayton, Ohio.

On May 25th, Sir Roy Fedden will deliver the 32nd Wilbur Wright Memorial Lecture before the Royal Aeronautical Society on "Aircraft Power Plants—Past, Present and Future," tracing the progress from your own remarkable engine of 1903 to engines of more than two hundred times the power now being used.

The Council and all members send you their heartiest greetings on this occasion with a feeling of confidence that when one of your countrymen delivers his lecture before the Society in 1945 it will be in an atmosphere of optimism for the future of the world and for the opening of that era of peace of which the aeroplane will be the greatest factor.

ARTHUR GOUGE,
President, Royal Aeronautical Society.

And had received the following reply:—

Arthur Gouge, President.

27th May, 1944.

Greetings to Council and members assembled for Wilbur Wright Memorial Lecture and to Sir Roy Fedden whom I remember with pleasure. I confidently hope the next months bring you relief from the strains so courageously endured in recent years

ORVILLE WRIGHT.

He now had great pleasure in calling upon Sir Roy Fedden to deliver his lecture.

AIRCRAFT POWER PLANT—PAST AND FUTURE

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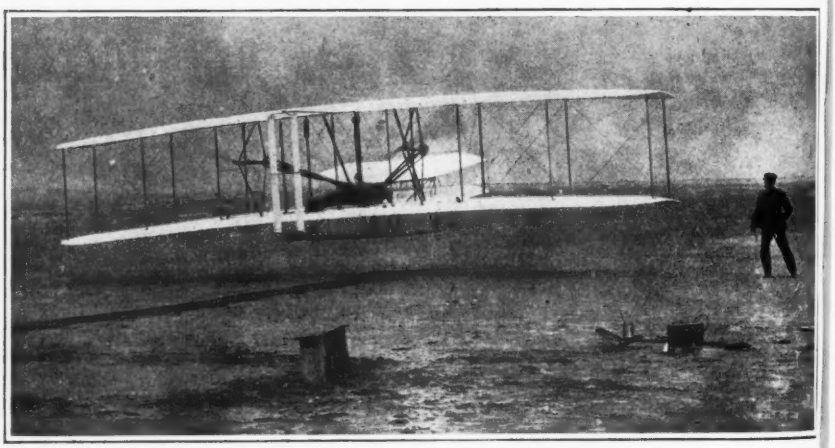
2. Historical review of early aero engines.
3. Aero engine advance during the war of 1914-1918.
4. Twenty years of aero engine development, 1919-1939.
5. Present reciprocating engines and power plants.
6. Fuels and lubricating oils for the future.
7. Post-war reciprocating engines and power plant.
8. Materials used in aero engine manufacture and possible future developments.
9. Aero engine ancillary equipment.
10. Propellers.
11. Future policy on gas turbines.
12. Conclusions.

Section 1.—Introduction.

I am deeply appreciative of the great honour bestowed on me by the Council of this Society by inviting me to give the 32nd Wright Memorial Lecture. Not only is this the most important annual event of the oldest institution in the world devoted entirely to the subject of Aeronautics, but for many years it has been the means of forging a close link with our great ally America, and has made possible an ever-growing bond of friendship between the aircraft fraternity of our two countries.



The first controlled and sustained flight, December 17, 1903, Orville Wright piloting the machine; Wilbur Wright on foot.

These lectures have been held without a break since their inception, even during the two wars, and this is the fifth to be given during the present period of hostilities. I would add that it is my sincere hope that we may have reason to believe that the American who follows me next year will not be adding a sixth. At the outset I would state that, although my remarks have been approved by

the Censor, any statements or opinions I may put forward are only my personal views, and do not necessarily represent those of any official department.

My subject this evening deals with the internal combustion engine, about which only recently it has been publicly stated that it would have been better for the good of the world if it had never been invented at all.

Although history may prove the aeroplane to be the most powerful single weapon in this present struggle, I feel that to lay the blame of causing wars at its door is a wrong and defeatist attitude to take up, and that we must look to the human qualities of greed, ambition, and lust of power, as being responsible, rather than the internal combustion engine. On the contrary, it has proved to be an increasingly faithful servant to mankind, and with the unbounded expansion of civil air transport anticipated after the war, in which this prime mover will play such a major part, I see every prospect of limitations and distances being so broken down that, if we can only have the right people at the helm to steer a clear and definite course during the next 25-30 years, this globe will be turned into such a small intimate place, that wars will be made an absurd impossibility.

The basic principles of flight by heavier than air machines, specifically enunciated by Lanchester and others, had for some years been awaiting a practical realisation by someone producing a light enough, and compact enough, prime mover. The gallant attempts by Maxim in this country with steam, and by Manly in America, with a five-cylinder radial internal combustion engine, the latter being an outstanding effort for its time, which was abandoned through no fault of the designer, give some indication of the difficulties of the problem at the dawn of this century.

Practical realisation of mechanical flight was achieved by the Wright Brothers in America some 40 years ago, by means of a four-cylinder in-line liquid-cooled petrol engine, which they had to design and construct themselves. It would be no exaggeration to say that all through the intervening 40 years, each stage of advancement of aircraft has been waiting on an improvement in the prime mover, but I do not think that, except perhaps in the earliest days, the aircraft designer has had to wait long for the right answer, and I have confidence that the appropriate power plant will be available for him when wanted in the future.

For nearly 30 years of this period it has been my good fortune to be connected with aircraft power plant, and to watch its development, which has been one of the most intriguing and outstanding efforts of mechanical endeavour in history, insomuch as the demand for light weight, compactness, and precision technique has been so insistent, that it has given the engine designer an opportunity and spur to employ ingenuity, methods of manufacture and materials, that would have been prohibitive from a commercial aspect in any other branch of engineering.

Interesting and instructive though this period has been, when looking back over it in retrospect, and considerable though the achievements have proved to be, most of the urge has been inspired by fear, and in preparation for war. Technically we are, I believe, on the threshold of an even more interesting period of enfoldment in the history of power plant for aircraft, and with the steady but inevitable step up in aircraft speed, it is essential to evolve a prime mover that is even more intimately concerned with, and closely woven into the structure of, the aircraft itself.

This country has for a number of years now taken a leading place in aircraft power plant development, and we must see to it that we continue to do so in the future, but we must also be certain, and take steps to ensure, that the new vistas which will unfold shall be for civil transport advancement and policing purposes, and not for a new race in armaments. The most practical way of doing this, in my opinion, is to provide a large enough team of highly trained, keen and enthusiastic engineers, with ample modern research and development equipment, and above all things, to be sure we maintain our technical superiority.

It is proposed in this paper to endeavour to trace the development of aircraft power plant over a period of 50 years, outlining some of the milestones of the past, and suggesting certain possible lines of development for the future.

SECTION 2.—HISTORICAL REVIEW OF EARLY ENGINES.

Although the Wright Brothers made their first classic flight in 1903, little was heard of aeroplanes or aeroplane engines for the next five years, and it was not until they came to Europe in 1908, and the now famous series of aeroplane meetings took place in this country and on the continent, during the years 1908-1910, that aircraft became sufficiently of a business to interest substantial engineering firms in the production of aircraft power plant. Previous to this date the initiative in this direction had mostly been centred in the small experimenter.

As soon as the internal combustion engine had proved its worth as a prime mover for aircraft, one would naturally have expected to see the large motor manufacturers become the most important competitors in this new field. The demand for aircraft power plant coincided, however, with the first boom in motor car production, and it is interesting to see the resultant reaction on the motor car industry in the different countries.

In England, with one or two exceptions, and especially in America, the motor car industry was too busy with cars to worry itself with aircraft engines, and the few developments which were initiated were mostly in the hands of small specialist firms. In France, where there was a great interest in aero engines, the then virile motor car industry was more serious about the matter, but even so the most successful aero engines of the period were produced by specialist firms, while in Germany the automobile companies tackled the problem very seriously.

By 1910 a large number of firms throughout Europe were producing aero motors experimentally, and a few in small scale production. J. S. Critchley's paper on " Motors for Aerial Navigation," given before the Institution of Automobile Engineers that same year, includes a list of over seventy firms making in-line, radial, and rotary engines.

Owing to the extreme flimsiness of the braced wire wooden construction of airframes of that period, the somewhat heavy, slow running, conventional in-line four and six-cylinder engines were not popular, since they brought about vibration problems in the fuselage and propeller, and the Gnome air-cooled rotary type of engine, with its light weight, even torque and high moment of inertia, became very popular with both British and French pilots. Race meetings on small closed circuits, such as at Rheims and Blackpool, cross-country races such as from London to Manchester, and Government aero engine competitions became the order of the day, and there was between 1910-1914 considerable rivalry and interest in aero engines, chiefly of an amateur and sporting nature, but already with an undercurrent of war potentiality; hence the British, French and German Army engine competitions of the period. Fig. 1 shows a tabulation of the engine used at the Rheims meeting. France held a leading position with a variety of types at the outbreak of the last war, and it will be seen that the Gnome had the best power/weight ratio.

The British Army competition was won by the Green Engine Co., but engines of foreign origin such as the Gnome, Renault and Austro-Daimler became the most popular in this country. The recently established Royal Aircraft Factory, having embarked upon their own designs, did not encourage matters at home. In Germany the famous car makers, Benz, Mercedes-Daimler and Austro-Daimler were the leaders, the former having won the German military competition.

Fig. 2 gives a representative list of the early aero engines of the different countries in 1914 that had reached the practical flying stage. Entirely experimental projects, many of which were particularly novel and interesting have been considered too numerous to include.

1909.

RHEIMS AVIATION MEETING.

Make.	Type.	Stated H.P.	Cooling.	Number Entered.	Cylinders.	Weight.	Wt./H.P.	M.E.P.
Wright	Vertical	30	W	7	4	176	6.9	80.5
Antoinette	Vee	24	W	1	8	92	4.8	69.2
,,	,,	50	W	6	8	209	5.2	74.0
R.E.P.	Radial	30	A	4	7	150	5.0	73.5
Anzani	,,	20	A	3	3	156	7.8	48.3
E.N.V.	Vee	60	W	2	8	286	5.8	68.3
Gnome	Rotary	34	A	1	5	132	3.3	60.0
Gobron	Radial	50/60	W	1	8	330	7.0	56.7/8
Itaia	Vertical	50	—	1	—	—	—	—
No name	,,	50/60	—	12	4/8	—	—	—

FIG. 1.

Tabulation of most important engines used at first aeroplane race meeting, Rheims, 1909.

REPRESENTATIVE ENGINES PRE-WORLD WAR I PERIOD.

Engine.	Country of Origin.	Layout and No. of Cylinders.	Cooling.	Bore (in.).	Stroke (in.).	B.H.P.	Weight (lb.).	Spec. Wt., (lb. B.H.P.)
E.N.V.	Gt. Britain	Vertical V8	Liquid	3.74	6.5	100	450	4.5
Wolseley	,,	,,	,,	4.0	5.5	90	385	4.39
Green	,,	Vertical inline 4	,,	5.52	5.75	60	260	4.34
,,	,,	,, ,, 6	,,	5.51	5.98	120	447	3.74
R.A.F.	,,	Vertical V8	Air	3.94	5.51	90	—	—
Sunbeam	,,	Vertical inline 8	Liquid	3.54	5.92	150	480	3.2
N.E.C.	,,	,, ,, 6	,,	3.69	4.5	90	320	3.56
A.B.C.	,,	,, ,, 6	,,	3.75	3.12	45	175	3.90
Anzani	France	Radial 6	Air	4.13	4.72	60	176	2.92
,,	,,	,, 10	,,	4.13	5.51	110	300	2.72
Salmson	,,	,, 9	Liquid	4.72	5.51	110	465	4.23
,,	,,	,, 9	,,	5.51	6.69	240	968	4.02
Clerget	,,	Rotary 7	Air	4.72	5.91	85	216	2.7
,,	,,	,, 9	,,	4.72	5.91	110	395	3.58
Renault	,,	Vertical V8	,,	3.78	4.72	70	396	5.65
,,	,,	,, V12	,,	3.78	5.51	100	639	6.39
Gnome	,,	Rotary 5	,,	3.94	3.94	34	132	3.9
,,	,,	,, 7	,,	4.33	4.73	50	172	3.44
,,	,,	,, 7	,,	4.88	5.52	80	207	2.59
Le Rhone	,,	,, 7	,,	4.13	5.51	60	183	3.07
,,	,,	,, 9	,,	4.13	5.51	80	253	3.16
Antoinette	,,	Vertical V8	Liquid	4.33	4.13	67	200	3.1
Chenu	,,	Vertical inline 6	,,	4.33	5.12	80	254	3.18
Curtiss	American	Vertical V8	,,	4.0	5.0	80	285	3.56
Hall Scott	,,	,, ,,	,,	4.0	4.0	80	290	3.63
Argus	Germany	Vertical inline 4	,,	5.51	5.51	100	348	3.48
Austro-Daimler	,,	,, ,, 6	,,	4.72	5.51	90	316	3.51
,, ,,	,,	,, ,, 6	,,	5.12	6.89	120	575	4.8
Benz	,,	,, ,, 4	,,	5.12	7.09	103	345	3.34
,,	,,	,, ,, 6	,,	4.57	6.30	108	425	3.94
Mercedes-Daimler	,,	,, ,, 4	,,	4.72	5.51	70	308	4.4
,, ,,	,,	,, ,, 6	,,	4.72	5.51	100	444	4.44

FIG. 2.

Tabulation of representative aero engines in use prior to the war, 1914-1918.

Designs naturally varied very much indeed in these early days, some being somewhat spidery and flimsy in an effort to obtain lightness, while others showed the technique of their stable by soundness and cleanliness of design. It will be useful to illustrate a few typical examples.

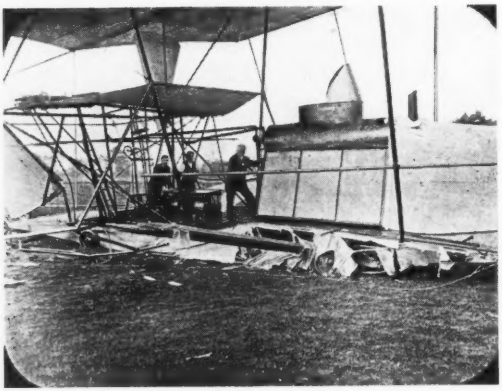


FIG. 3.

Maxim's steam-driven aircraft, 1873, after its crash.

Fig. 3 shows the Maxim experimental steam propelled machine photographed immediately after its crash in 1893, with the designer, Sir Hiram Maxim, standing by the side of the tubular boiler. Twin 2-cylinder compound engines were fitted.

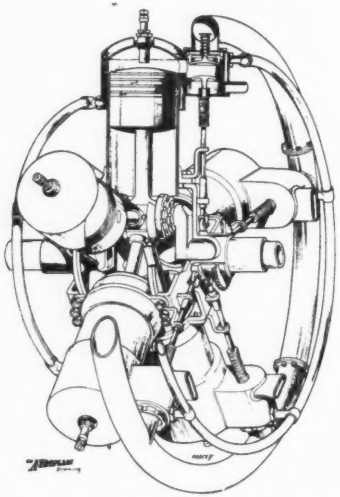


FIG. 4.

Diagram of Manly 5-cyl. radial engine used in Langley aircraft, 1903.

Fig. 4 shows the American Manly five-cylinder radial liquid-cooled engine of 1903, a most outstanding effort of 52 h.p. for 151 lb. weight. This can be said to be the first internal combustion engine to be designed primarily for aircraft propulsion, and the reason why it has not received greater recognition is that the aeroplane, which was launched from a houseboat, crashed on both the initial attempts at flight.

In contrast, Fig. 5 shows the eight-cylinder V Antoinette engine of 67 h.p. produced in 1908. Designed by Levavaseur, this engine also was a classic type, many years before its time, and had copper deposited jackets, steam cooling and direct fuel injection.

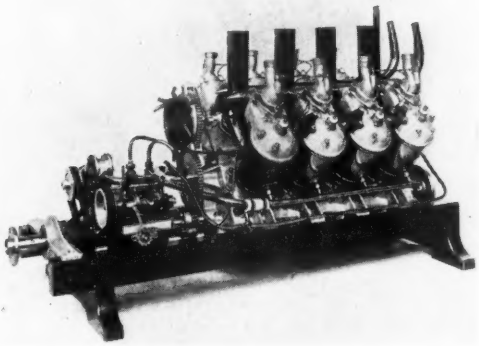


FIG. 5.
Antoinette steam-cooled 8-cyl. V. 70 h.p. engine with direct fuel injection, 1908-1910.

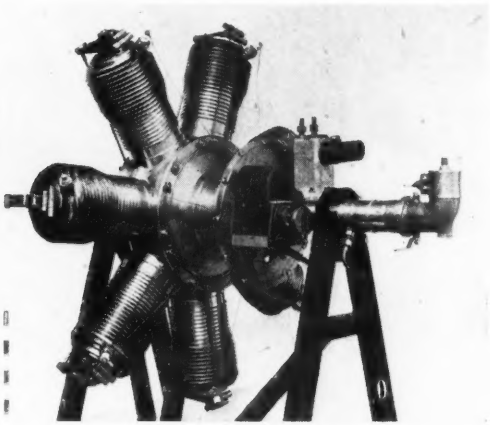


FIG. 6.
Gnome 50 h.p. air-cooled 7-cyl. Rotary, 1910.

Fig. 6 shows the 50 h.p. Gnome, machined all over and made from steel forgings, a quite novel and unique technique in those days. Fig. 7 shows the 80 h.p. V air-cooled Renault, while Fig. 8 shows the 70 h.p. six-cylinder in-line German liquid-cooled Mercedes-Daimler, a very clean and successful design and Fig. 9 the 120 h.p. Austro-Daimler engine with copper deposited water jackets.

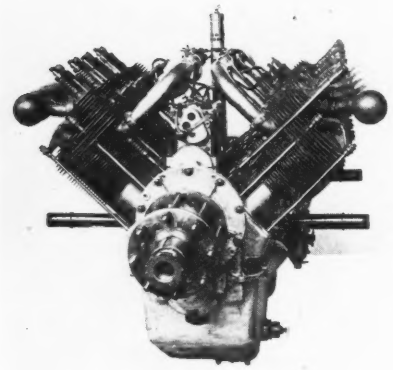


FIG. 7.
Renault 80 h.p. air-cooled 8-cyl. V., 1912.

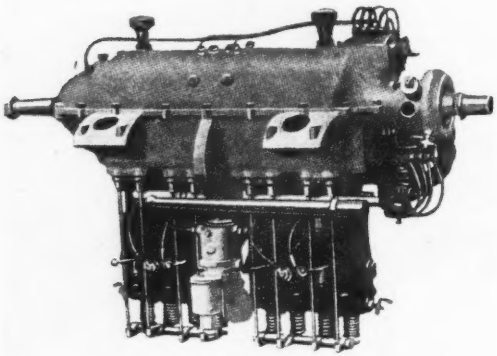


FIG. 8.
Mercedes 70 h.p. liquid-cooled 4-cyl. in-line inverted, 1912.

Even in those early days the desire for even torque, and the elimination of vibration, in conjunction with relatively high power, was seen in engines with a large number of cylinders; mostly, however, made in very small numbers for racing purposes. What were, in those days, high horse-power engines of 200-400 h.p., however, were actually racing in prototype form in the summer of 1914, including 14-cylinder rotary air-cooled, 20-cylinder static radial air-cooled, 18-cylinder radial liquid-cooled and 16-cylinder in-line liquid-cooled, mostly of French origin.

Little or nothing was known about fuel except the colour of the cans in which it was sold, carburation was very crude, and ignition and plugs bad; hence, poor distribution and rough running in the air. Light alloys were in an undeveloped state, aluminium pistons unknown, as also were monobloc aluminium castings, and as air speeds were low, cooling problems were severe, and detonation and rough running on the light airframe structures serious.

All these factors in combination go to show clearly why the light, smooth running air-cooled rotary with a considerable flywheel effect up to powers of 100 h.p. was the most popular power plant with the sporting fraternity, and carried off the cream of the races and competitions. As has always been the case, accessibility and maintenance were important problems in these early machines. The rotary, although only having a life of about 30 hours between overhauls, could be dismantled from the airframe readily as a complete unit, and owing to its design and construction, easily stripped, and quickly overhauled and refitted with certainty.

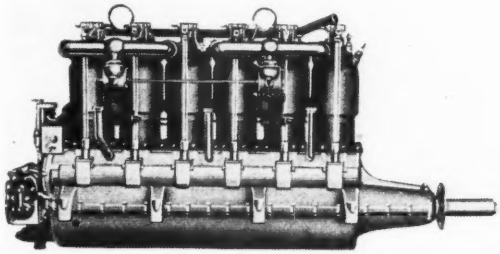


FIG. 9.

Austro-Daimler 120 h.p. liquid-cooled 6-cyl. in-line, 1912 (called Beardmore when made in England).

The present day engineer has so many aids to his art that I am inclined to think that the difficulties of these early pioneers are not now fully appreciated, and that what they did actually accomplish with the tools available to them was quite remarkable. It must be remembered that in the first few years of the present century, engineering materials were in an entirely different state of development from what they are to-day: aluminium alloys were crude and quite unknown for highly stressed parts working at high temperature, such as pistons: high quality alloy steels, free from impurities, had not yet come into general use, and nitriding and other means of high precision hardening were unknown. Modern precision machine tool operations ensuring accurate limits and the elimination of vibration, so important to the light-weight, highly stressed aero engine, were also in their infancy, and accurate gear cutting and subsequent grinding of the teeth, honing, lapping and fine boring were all unknown, while gauging, inspection and testing procedures, all of which have now been standardised, were then much more haphazard. If the present day aero engine designer, therefore, will for a minute consider what his problem would be were he shut off from all these aids and appliances, I think he will appreciate some of the problems which confronted the early pioneers.

SECTION 3.—AERO ENGINE ADVANCE DURING THE WAR OF 1914-1918.

It will be appreciated that by 1914 there was a considerable number of firms in Europe, and a few in America, developing aero engines, although it could not be said that any of them were in large series manufacture on anything like the scale of current automobile production. In June, 1914, the motor car firm

with which I was connected, became interested in aero engine manufacture, and I went over to the Continent and inspected the Renault and Clerget aero engine works in Paris, and then went on to Germany, where I visited the Mercedes-Daimler works and saw some forty to fifty six-cylinder liquid-cooled in-line engines all together in one shop, which was a very large number of engines in those days.

At the outbreak of war in August, 1914, the Royal Flying Corps had four operational squadrons only, and very few aircraft—something of the order of forty to fifty—went to France with the Expeditionary Force in the following month. In the early part of the war aeroplanes were used chiefly for scouting and artillery spotting, and there was no intensive air war until the spring of 1916. Time was therefore available for the most important motor car firms in Britain to be drawn into aero engine manufacture, either on designs of their own, as in the case of Rolls Royce and Napier, or on a Royal Aircraft Factory or French rotary design, as in the case of Daimler and Lanchester. The first period of the war therefore saw the belligerents chiefly using aircraft for minor tactics, relying on engines of 70-120 h.p. It is worth mentioning here the speed at which these comparatively simple aero engines were produced in the last war. The American Liberty is stated to have been designed, made and to have run a 50-hour test in three months in 1917, and certain British types were designed, developed and put into production successfully in under two years.

In the early stages the British chiefly used air-cooled rotaries of French origin, many of which were built in this country, including Gnome, Clerget and Le Rhone types, air-cooled in-line V engines of eight cylinders, designed by Renault and the Royal Aircraft Factory, and the 120 h.p. Beardmore liquid-cooled in-line engine of Austro-Daimler origin. Certain other types enumerated in the first tabulation were also used, but those named bore the main brunt of the early work.

At the outbreak of hostilities, the French relied considerably on their own air-cooled rotaries, Gnome, Clerget and Le Rhone, but air-cooled in-line Renault, liquid-cooled radial Salmson, and air-cooled radial Anzani engines, were also employed. Germany, who had a better supply of aero engines in the early period of the war than we possessed, relied upon a sound range of large volume slow running liquid-cooled six-cylinder in-line engines, which had been extensively developed as a result of the 1912 German aero engine competition, including the Benz, Mercedes-Daimler, and Austro-Daimler. Prior to the entry of America into the war, the Curtiss Co. developed and exported a considerable quantity of 80 h.p. V8 liquid-cooled engines to Great Britain which, after modification in this country, gave good service. During the last two and a half years of hostilities all branches of the air war developed very extensively, and entailed a relatively large aero engine production in all the belligerent countries.

In Britain a number of new and more powerful designs were produced, developed and tested out, but over the latter and most intensive period of the war we relied mainly on the following types for the major portion of our effort:—

Rolls Royce Falcon, 280 h.p., V.12, water-cooled;
Rolls Royce Eagle, 365 h.p., V.12, water-cooled;
Wolseley-Hispano Viper, 220 h.p., V.8, water-cooled;
Siddeley Puma, 240 h.p., six-cylinder water-cooled;
Bentley, 240 h.p., nine-cylinder air-cooled rotary.

In France the air-cooled rotaries were increased in power to their limit, and Hispano, Renault, and Lorraine-Dietrich developed liquid-cooled in-line V engines, the former producing a series of V.8 engines, which were used in large numbers.

In Germany the policy of gradually stepping up and increasing their series of liquid-cooled in-line six-cylinder engines was continued. Mercedes-Daimler

made an eight-cylinder in-line, and Austro-Daimler and Maybach V.12 liquid-cooled in-line types. For the ultimate intensive period of the fighting, the Germans relied almost entirely on six-cylinder in-line liquid-cooled engines of 250-300 h.p.

ENGINES IN OPERATION AND TRAINING USE DURING WORLD WAR I.

Engine.	Country of Origin.	Layout and No. of Cylinders.	Cooling.	Bore. (in.).	Stroke. (in.).	B.H.P.	Weight (lb.).	Spec. Wt. (lb./B.H.P.)
R.A.F. 1A.	Gt. Britain	Vertical V8	Air	3.94	5.51	100	461	4.61
„ 3A.	„	„ V12	Liquid	4.5	5.5	260	780	4.85
„ 4A.	„	„ „	Air	3.94	5.5	140	680	4.85
Rolls-Royce Falcon III.	„	„ „	Liquid	4.0	5.75	220	695	3.16
Rolls-Royce Eagle III.	„	„ „	„	4.5	6.5	285	900	3.16
„ „ „ VIII.	„	„ „	„	4.5	6.5	360	925	2.58
Beardmore	„	Vertical 6	„	5.12	6.89	120	545	4.54
„	„	„ 6	„	5.59	6.89	160	592	3.7
Sunbeam Arab	„	„ V8	„	4.72	5.12	200	517	2.58
„ Maori	„	„ V12	„	3.94	5.31	250	920	3.68
„ Cossack	„	„ „	„	4.33	6.3	320	1200	3.75
Siddeley	„	Vertical inline 6	„	5.71	7.48	240	625	2.5
Bentley	„	Rotary 9	Air	4.72	6.69	160	405	2.6
„	„	„ 9	„	5.51	7.09	240	498	2.08
Renault	France	Vertical V8	„	3.78	4.72	70	396	5.65
„	„	„ „	„	4.13	5.12	80	463	5.78
„	„	„ V12	„	4.13	5.12	130	772	5.94
„	„	„ „	Liquid	4.13	5.51	220	855	3.9
Gnome Monosoupape	„	Rotary 9	Air	4.88	5.90	100	297	2.97
„	„	„ 14	„	4.88	5.52	160	396	2.40
Clerget	„	„ 9	„	4.72	6.3	110	367	3.3
„	„	„ 9	„	4.72	6.3	130	400	3.1
Le Rhone	„	„ 9	„	4.13	5.51	80	245	3.05
„	„	„ 9	„	4.41	6.69	110	323	2.93
„	„	„ 14	„	4.13	5.51	120	375	3.12
Hispano	„	Vertical V8	Liquid	4.72	5.12	150	445	2.90
„	„	„ „	„	4.72	5.12	180	510	2.84
„	„	„ „	„	5.51	5.91	300	796	2.65
„	„	„ „	„	4.72	5.12	180	445	2.61
Anzani	„	Radial 6	Air	4.13	4.72	60	176	2.94
„	„	„ 10	„	4.53	5.91	125	460	3.68
Salmson	„	„ 9	Liquid	4.73	5.52	135	465	3.44
„	„	„ 14	„	4.73	5.52	200	660	3.3
„	„	„ 9	„	5.51	6.69	300	980	3.26
Lorraine Dietrich	Germany	Vertical V8	„	4.72	6.69	342	770	2.25
Curtiss OX	American	„ „	„	4.0	5.0	90	285	3.18
„ VX	„	„ „	„	5.0	7.0	180	540	3.0
Hall Scott	„	Vertical inline 6	„	5.0	7.0	200	530	2.65
Liberty	„	Vertical V12	„	5.0	7.0	400	855	2.11
Fiat	Italy	Vertical inline 6	„	6.3	7.09	260	928	3.56
Isotta Fraschini	„	„ „ 6	„	5.51	7.09	250	620	2.48
Mercedes	Germany	Inverted inline 4	„	6.3	6.69	70	240	3.4
„	„	Vertical inline 6	„	4.13	5.51	120	312	2.6
„	„	„ „ 6	„	5.51	6.3	240	900	3.75
„	„	„ „ 6	„	6.3	7.09	300	936	3.12
Benz	„	„ „ 6	„	4.57	6.30	108	425	3.94
„	„	„ „ 6	„	5.12	7.09	160	475	2.97
„	„	„ „ 6	„	5.71	7.48	275	816	2.97
Austro-Daimler	„	„ „ 6	„	5.31	6.89	240	728	3.03
Maybach	„	„ „ 6	„	6.5	7.09	300	921	3.08
B.M.W.	„	„ „ 6	„	6.3	7.5	260	732	3.05
Oberursel	„	Rotary 11	Air	4.88	5.51	150	428	2.86
Siemens Halske	„	„ „ 11	„	4.88	5.51	160	435	2.72

FIG. 10.

Tabulation of representative engines in operational and training use during the war, 1914-1918.

In America the outstanding effort was the Liberty engine, developed by a group of motor manufacturers headed by Colonel Vincent, of Packards, as the Chairman of the Technical Committee. A very large programme was laid down for these engines, but inevitable technical difficulties delayed the schedule, and

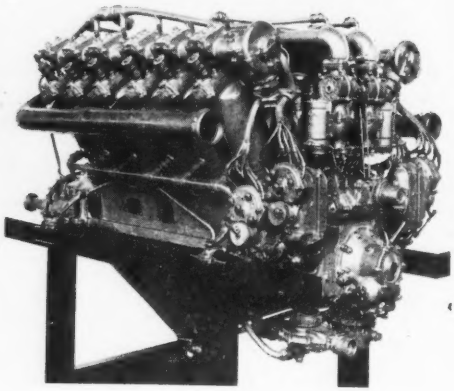


FIG. 11.

Rolls Royce Eagle VIII 360 h.p. liquid-cooled 12-cyl. V. in large series production at the end of the last war.

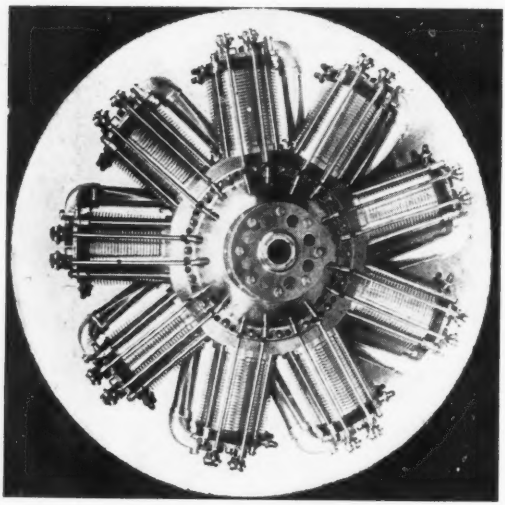


FIG. 12.

Bentley B.R.2 240 h.p. air-cooled 9-cyl. Rotary in considerable operational use at the end of the last war.

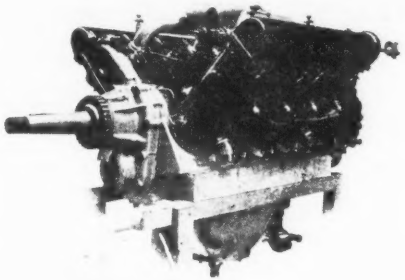
only comparatively small numbers reached this country for installation in British machines in the summer of 1918. A large flow, however, was commencing at the time of the Armistice. The Hispano engine was made in large quantities in America and exported to France and England.

Fig. 10 shows in tabular form representative types of engines produced in quantity in different countries during the war 1914-1918. The number of experimental types is so large that it would confuse the issue to include all that were made, and only those which were produced to any extent have been selected.

Some of the more interesting engines of this period are illustrated. Fig. 11 shows the Rolls Royce Eagle, a 12 cylinder V liquid-cooled engine of 360 h.p. Important features are the overhead camshaft, separate cylinders with welded steel jackets, four magnetos and dual Hobson carburettor.

Fig. 12 shows the other outstanding British type, the Bentley 9 cylinder air-cooled rotary of 240 h.p. One can appreciate the clean, robust design and good finish of this engine, which had a power/weight ratio of just over 2 lb./h.p., and which was used in many of our fighters in the latter part of the war.

Fig. 13 illustrates the Model D Hispano liquid-cooled 90° V engine of 400 h.p. is shown in Fig. 14. The cylinders, which were machined from steel forgings, were welded together in pairs, and a common sheet metal water jacket was provided for each pair. Aluminium pistons were used, and an overhead camshaft operated the inclined valves through rockers.



The Model D Hispano-Suiza Engine.

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FIG. 13.

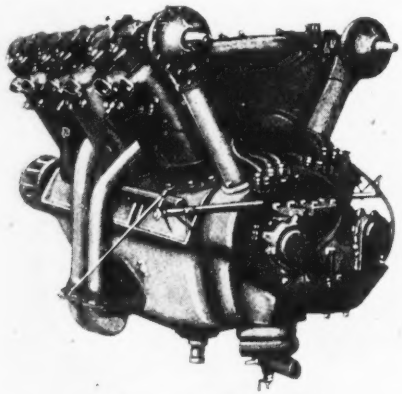
Hispano 200 h.p. liquid-cooled 8-cyl. V., the premier French engine of the last war.

Fig. 15 shows the 8 cylinder in line liquid-cooled Mercedes of 300 h.p. This engine, which was brought to this country immediately after the Armistice, represented the latest German wartime technique, and the large bore cylinders, overhead camshaft and propeller reduction gear will be noted.

Another representative of the German form of construction is provided by the Maybach 300 h.p. 6 cylinder in line liquid-cooled engine, illustrated in Fig. 16. Based on their earlier designs of airship engines, this more powerful type was developed primarily for aeroplane installation. Steel cylinder barrels with screwed-on cast iron heads were used, and the water jackets were machined all over from steel forgings.

Finally in this selection we have the American Liberty engine, shown in Fig. 17. This 12 cylinder V liquid-cooled unit of 400 h.p. was of rugged and simple design, with separate cylinders and battery ignition, the distributors being mounted at the rear ends of the overhead camshafts.

Operational machines did not employ superchargers, although these were made and tested out experimentally, notably at Farnborough by the Royal Aircraft Factory, which by this time had been re-organised and was known as the Royal Aircraft Establishment. A very few French Hispano engines with Rateau turbo superchargers are stated to have been used in combat towards the end of the war.



The Lorraine Dietrich Type 13.

FIG. 14.

Lorraine Dietrich 400 h.p. liquid-cooled 8-cyl. V., in use by the French in the last war.

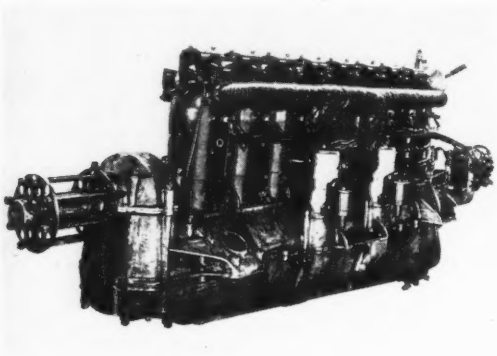


FIG. 15.

Mercedes 300 h.p. liquid-cooled 8-cyl. in-line, with geared propeller, in use by the Germans at the end of the last war.

When reviewing the plethora of divergent designs of experimental engines produced between the two wars, it is interesting to recall the project work of the undoubted Brains Trust which existed at Farnborough in the years 1914-1916, during which time many of these new types which later saw the light of day in

practical form, were initiated, and in several cases actually laid out by this group. It would seem, therefore, that there is nothing new under the sun, even in aero engines.

A few engines, notably Rolls Royce in this country, used gearing for their propellers, but most of them had direct drives. 18,000-20,000 ft. was a high operational altitude, and problems were already present on carburation and distribution, which were very poor indeed, in combination with the rapid loss of power of the naturally aspirated engine. A good deal of trouble was experienced with ignition and plugs. Magneto manufacture was one of the most difficult problems, as this country had relied mainly on the products of the German Bosch Company before the war. Cylinders were mostly of the separate welded steel type with either copper or sheet steel jackets, while radiators were somewhat crude and there was a fair amount of trouble with liquid cooling.

Cast aluminium pistons were developed in series production during the war, mostly using an 8 per cent. copper alloy. Towards the end of hostilities Y alloy was developed by Dr. Rosenheim, of the N.P.L., but aluminium casting technique

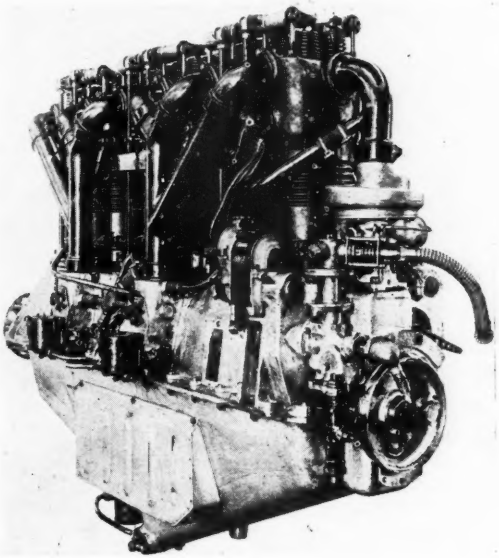


FIG. 16.

Maybach 300 h.p. liquid-cooled 5-cyl. in-line, in use by the Germans at the end of the last war.

generally was not good, die castings, permanent mould and stripping plate patterns being unknown. There were no aluminium forgings used in aero engine manufacture during this period.

During the first world war it might be said that the initiation of the precision aero engine into series production was successfully accomplished, and although the output of aero engines from each country was very different from what is being realised to-day, nevertheless it was much greater than had been attempted or thought possible before. Considerable progress was made in the drawing up of steel specifications, the selection and testing of casts of steels, improvements

in drop forgings, heat treatment of alloy steels for crankshafts, connecting rods, etc., and test piece and analysis procedure.

During the few years immediately preceding the war, a series of alloy steels had been produced for motor car work, primarily for gears and transmission shafts. These were further developed, and new Air Board specifications were issued in collaboration with the Aeronautical Inspection Department and the British Engineering Standards Association. Considerable improvements were made in the methods of production, a full range of limit and screw gauges was introduced, a proper inspection procedure was initiated, and a schedule and efficient equipment for the testing and acceptance of aero engines laid down. In fact it may be said that during this war aero engine manufacture grew up from being the specialised province of the experimenter into a national precision industry.

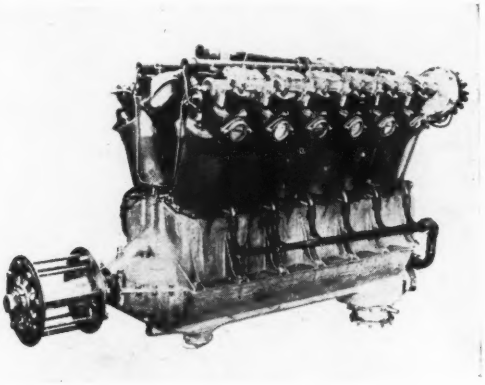


FIG. 17.

Liberty 400 h.p. liquid-cooled 12-cyl. V., in large production in America at the time of the Armistice, 1918.

In connection with many of these matters, invaluable work was accomplished by a small band of stalwarts, including Aitchison, Bulman, Philpott, Ross Verney, and several others, who, during this period, laid the foundations which did so much to uphold British aero engine prestige in later years.

Anyone who is interested in the narrative of British power plant should not fail to read the early chapters of Volume 6 of "The Official History of the Last War," where the author, H. A. Jones, so frankly and in considerable detail discusses the problems of the Air Board, in obtaining the necessary number of aero engines to meet our various theatres of war. The student of history will find interesting comparisons between the two wars in this respect, particularly in regard to putting engines into series production before bringing them to a reliable stage of development.

SECTION 4.—TWENTY YEARS OF AERO ENGINE DEVELOPMENT, 1919-1939.

The end of the first twentieth century war saw all the major belligerent countries with firmly established aero engine industries, well set-up development facilities and a large production potential. Great increases in power output from a single engine had been achieved and there were many interesting technical developments approaching fruition. With the cessation of hostilities there came a natural reaction to war, and a general desire for disarmament. This was coupled with

a widespread feeling that the aeroplane had already caused enough trouble and was something not to be encouraged in a world at peace. Consequently there was a sudden fall in the curve of progress, and a great change in the orientation of the industry in all countries. At the end of the war the unfavourable commercial outlook led the majority of the large industrial undertakings which had entered the wartime production field, to revert to their pre-war activities and to abandon aero engine work altogether. Even so the few survivors had a hard struggle to keep going, especially in the early years.

In Britain, Rolls Royce, who had undoubtedly produced the best engines during the war, although retaining their interest in aero engine development, again concentrated their main efforts on motor cars. Napier's, on the other hand, who had also held a leading position in the motor vehicle world before the war, was the one established concern which took the opposite course, and continued to concentrate on aero engine work. This decision was influenced, no doubt, by the fact that, at just about the time of the Armistice, they had brought their W.12 liquid-cooled " Lion " engine of 400 h.p. to a successful state of development, and so had the most advanced British engine of the day. Armstrong-Siddeley followed a middle course, and continued with the development of their 14-cylinder two bank radial, concurrently with their motor car work. An exceptional course was taken by the Bristol Company which, although having been concerned only with airframe work, established an aero engine department to take over the development of the Cosmos Jupiter, which I had had the privilege of initiating with my colleagues at Brazil Straker's during the war. Another factor which influenced the British position was the establishment of the Aircraft Disposal Board with a large stock of engines which took some years to liquidate, and which undoubtedly had the effect of further depressing interest in peace time aero engine production.

The position in France was rather less acute than in this country, for, with her special geographic position, she had less inclination for immediate disarmament, and had not entered upon the difficult political times that ensued subsequently, and much more energy was therefore devoted to aero engine development. The Lorraine Dietrich Company dropped motor car manufacture in favour of their 12-cylinder liquid-cooled aero engine, which, like the Lion in this country, was the most up-to-date French engine at the time of the Armistice, and were able to continue in comparatively large scale production—some 1,200-1,500 engines per annum, a very ambitious programme in those days. Hispano also continued to make aero engines, and the Gnome Company, which had been so successful with rotaries, took out a licence for the Bristol Jupiter nine-cylinder Radial, and almost immediately secured large production orders. The French industry was live and progressive during the immediate post-war period, and pioneered many developments which have subsequently come into widespread use in other countries.

As part of the terms of the Peace Treaty, Germany was debarred completely from making aero engines. The only other country in Europe seriously concerned with aero engine development in the early years after the war was Italy, and here Fiat, Ansaldo and Isotta Fraschini, who all had promising designs at the time of the Armistice, continued development of their own types, while Alfa-Romeo took out a Bristol licence.

On the other side of the Atlantic, America dropped aero engine production almost entirely. The only concern to remain seriously in the field was the Curtiss group, one section of which, during the war, had started out to manufacture the Hispano engine. This combine produced liquid-cooled in-line engines at Buffalo, while the Wright Company made the Lawrence air-cooled radial at Paterson, New Jersey, and a 12-cylinder edition of the Hispano.

The hardest years for the aero engine industry in all countries were between 1919 and 1925, for military requirements were small, and, despite a great deal of

Engine.	No. of Cyls.	Bore × Stroke.	Swept Vol. (cu. ins.).	Output (B.H.P.)	Dry Wt. (lb.).	Spec. Wt (lb./B.H.P.
Beardmore Cyclone ...	6	8.562 × 12.0	4,145	840	1,800	2.14
Rolls Royce Condor ...	12	5.5 × 7.5	2,138	700	1,320	1.88
Napier Cub	16	6.25 × 7.5	3,681	1,075	2,400	2.23
Sunbeam Sikh	12	7.09 × 8.27	3,912	840	1,952	2.32
Galloway Puma Atlantic	12	5.71 × 7.48	2,298	575	1,150	2.00

FIG. 18.

Tabulation of Large Volume British engines under development soon after the last war, but later abandoned.

enthusiastic pioneer work, civil air transport had not attained sufficient propor tions to produce much business for the aircraft or engine constructor. This wa all most unfortunate for the advancement of technical progress, and resulte in the dropping of development work on a great number of valuable projects Immediately after the war, for instance, the British industry was in a very viril state, but, due to national policy, this could not be maintained and much promising work had to lapse. Fig. 18 gives particulars of some of the interesting large engines which were under development during the first few years, and were later abandoned. Most of these were on the large side for the powers they were intended to develop, and consequently the power/weight ratios were on the high side. Nevertheless, they serve to indicate the vision and initiative which was being displayed, and it is a great pity that all this had to be lost. We must take a lesson from this, and make sure that the technical development which is in hand to-day, and which is so important to the future of British aviation, does not meet a similar fate.

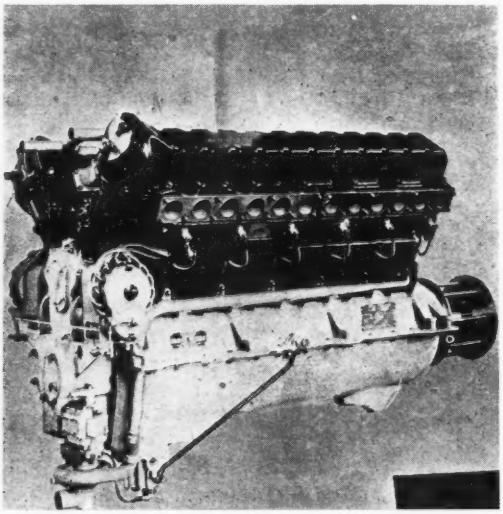


FIG. 19.

Curtiss D.12 600 h.p. liquid-cooled 12-cyl. V., winner of Schneider Trophy Race in 1925 for America, a classic type.

By 1925 there were signs of a revival of interest in aviation throughout the world, and this had its effect on aero engine development. In this country a great stir was caused in aviation circles by the Fairey Company, who in this year broke new ground by importing a number of Curtiss D.12 liquid-cooled engines from America (Fig. 19). About this time Rolls Royce designed a new high efficiency V.12 liquid-cooled engine known as the "F" type, having monobloc cylinder construction. This was the forerunner of the famous series—Kestrel, Peregrine, Merlin and Griffon—which has played so important a part in the superiority of our military aircraft, especially fighters, both before and during this war. The Kestrel is shown in Fig. 20.

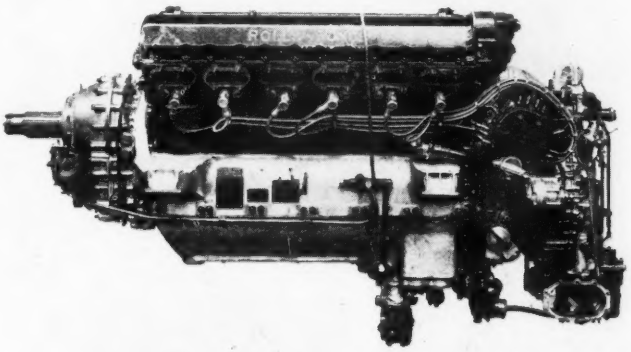


FIG. 20.

Rolls Royce Kestrel 550 *h.p. liquid-cooled* 12*-cyl. V.*

One of the greatest inspirations to the technical development of aero engines, particularly in this country and in Italy, was the Schneider Trophy races. It was after the race of 1925, which was won by America, with a Curtiss machine using a special D.12 engine of 600 h.p., that Britain began to take a real interest in the race as a means of advancing aircraft and engine design and performance. It would be fair to say that from this date onwards, the race had a profound influence on the history of the liquid-cooled engine in this country.

The Napier Company had produced a special racing version of the " Lion " engine as early as 1919, giving 470 h.p. for a specific weight of 1.9 lbs. b.h.p. This engine won the Aerial Derby three times, and also the Schneider Trophy in 1922. By 1927 the power had risen to 875 h.p. for a specific weight of 1.06 lb./b.h.p. and a compression ratio of 10:1, and the race in this year was won at Venice by a Supermarine machine fitted with it, at a speed of 281 m.p.h. The power output was especially good for an unblown unit. This engine had the highest thermal efficiency ever recorded in any heat engine up to that time. Subsequently, the performance was still further improved without changing the cylinder dimensions, and in 1933 it reached 1,450 h.p. for a specific weight of 0.76 lb./b.h.p. The 1927 engine is shown in Fig. 21.

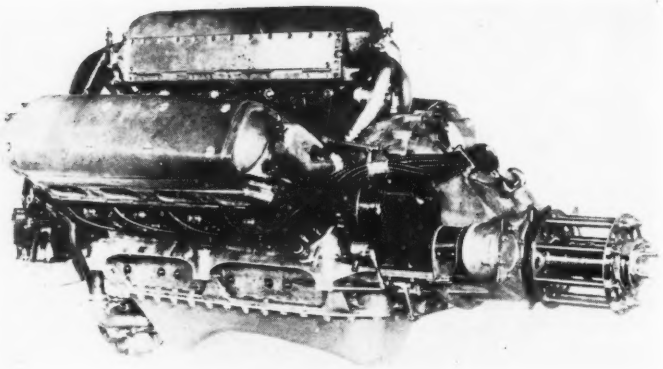


FIG. 21.

Napier Racing Lion 875 h.p. liquid-cooled 12-cyl. Broad Arrow type, winner of the Schneider Trophy Race at Venice, 1927.

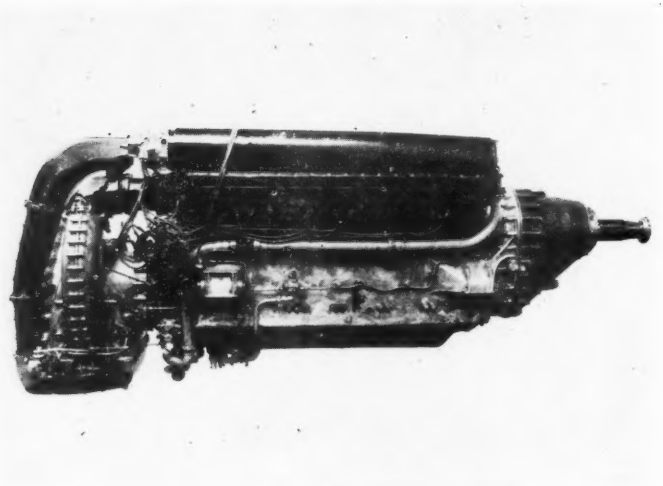


FIG. 22.

Rolls Royce " R " engine, liquid-cooled, 12-cyl. V., winner of the Schneider Trophy Races in 1929 and 1931—2,300 h.p.

In 1928 the British Government placed a contract with Rolls Royce for a special racing engine. For this the well proven V.12 layout was adopted, and a remarkable engine of 1,900 h.p. was produced, which, fitted to a Supermarine S.6 machine, won the 1929 Schneider Trophy race at a speed of 328 m.p.h. Further development ensued, and the engine fitted to the Supermarine S.6b aircraft which secured the Trophy outright for Britain in 1931, developed

2,300 h.p. for a specific weight of 0.71 lb./b.h.p. The same machine subsequently raised the World Speed Record to 407.5 m.p.h. The engine is shown in Fig. 22. The size of the blower is noteworthy.

Italy was the only other country to take an active place in the later Schneider Trophy races, and some very highly developed Fiat engines were produced for the purpose. Fig. 23 shows the 2,800 h.p. Fiat racing engine of 1931, which was arranged for driving contra-rotating propellers and obtained the World's Speed Record. This remarkable power unit, consisting of two V.12 engines placed end to end, had the propeller drive from the rear unit passing through the V and the propeller shaft of the front unit, which was the first practical application of the principle of counter rotation.

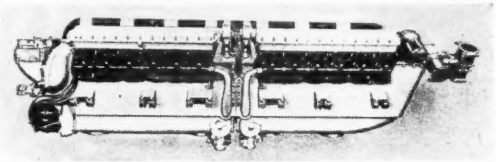


FIG. 23.

Italian Fiat 2,800 h.p. liquid-cooled 24-cyl. in-line, built for Schneider Trophy in 1931.

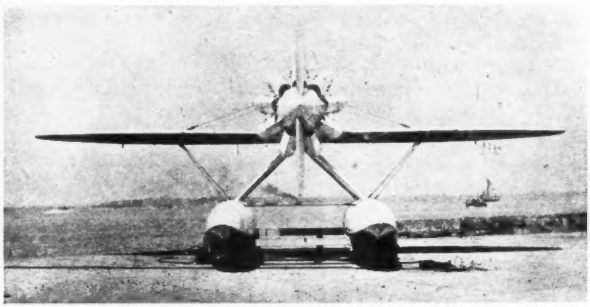


FIG. 24.

Front view of Short Crusader Schneider Trophy Machine with 800 h.p. Bristol Mercury air-cooled radial.

On the air-cooled side, the Schneider Trophy was not without its effect on engine development. One of the British machines prepared for the 1927 race was the Short "Crusader," fitted with a totally enclosed Bristol Mercury nine-cylinder radial racing engine, which gave it an excellent performance, but unfortunately, on assembly at Venice, the aileron controls were crossed, and it crashed shortly after take-off on its test flight. This power plant, which developed 808 h.p. for a specific weight of 0.85 lb./b.h.p., although in itself a special type, was the forerunner of the Mercury which has done such yeoman service in a number of our military aircraft. A front view of the "Crusader," showing how cleanly the engine was installed in a special helmeted cowling is given in Fig. 24.

By 1929 the results of the Schneider Trophy races had given such an impetus to the compact, high efficiency, supercharged, liquid-cooled engine that it became

clear that such engines in series form would have a considerable future for military work. It is noteworthy that even in America, where the air-cooled radial reigned supreme, General Motors acquired the Allison Company, which had specialised in racing motor car engines, although having had aero engine experience, and started work on the Allison V.12 liquid-cooled engine, which has been built in such large numbers for fighters during the present war.

Despite the success of the liquid-cooled engine in the Schneider Trophy races, however, the popularity of the air-cooled radial was by no means impaired for ordinary type civil and service aircraft, either in this country or abroad. In fact, with the increased tempo of engine development from 1925 onwards, the radial increased its influence everywhere. Most of the models then existing were of the nine-cylinder single bank type, although a notable exception was the Armstrong Siddeley Jaguar with 14 cylinders staggered in two banks. The acceptance of the nine-cylinder layout as a fundamentally sound type is, perhaps, well illustrated by the fact that the Bristol Jupiter was built under licence in no less than fourteen different countries. This engine was produced in a considerable number of types, and introduced into a large series production many features which have to-day become commonplace, such as mechanically driven supercharger, forged cylinder heads, forged pistons, forged crankcases and automatic boost control. It was used on a number of pioneer long distance flights, and it was also responsible for establishing a World's altitude record in a Junkers machine in 1927.

In America, Wright's made considerable progress with air-cooled radials. In 1925 a number of the technical staff of this concern broke away and began the aero engine division of Pratt and Whitney, which also started to design air-cooled radials, and in record time produced the now world famous nine-cylinder Wasp. Thereafter a tremendous impetus was given to civil aircraft power plant in America by keen competition between the two firms. The air-cooled radial, in fact, became the general purpose engine of all American aviation, being used in all of their Navy fighters as well as their bombers and long range seaplanes, and entirely " scooping the pool " for large airliners.

Since this time the air-cooled radial has been developed in every country concerned with aero engine manufacture, and as the need for greater and greater powers became evident, so a gradual change-over to double bank engines took place, the usual number of cylinders being fourteen. Before this became general practice, however, the single bank engine, due largely to the incidence of high octane fuels, was developed and improved to a degree which only a few years earlier had been thought impossible. For example, the Bristol Pegasus, of exactly the same capacity and layout as the Jupiter, produced over 1,000 h.p. for take-off in 1937 compared with 485 h.p. for the Jupiter of 1925. This engine held the World Altitude Record on three occasions, and also the long distance record in a Vickers Wellesley at the time of the outbreak of war

The Bristol Company meanwhile, anticipating that the time would eventually come when a limit to the development of the poppet valve engine would be set by valve materials, and by valve gear complications on double bank engines, started experimental work in 1927 on the Burt McCollum single sleeve valve mechanism. After many setbacks the system was brought to a satisfactory state of operation, and in the period under review four sleeve valve engines were designed and produced, and three were actually in course of being put into production in 1939. These were the Perseus, a nine-cylinder radial of the same capacity as the Mercury, and developing at that time 890 b.h.p., the Aquila a smaller nine-cylinder radial of 600 b.h.p., intended primarily for civil use, the Hercules, 14-cylinder two bank radial of 1,400 b.h.p., and the Taurus 14-cylinder two bank radial of 1,130 b.h.p., designed with special consideration for Fleet Air Arm requirements. The Perseus and the Mercury are shown side by side for comparison in Fig. 25.

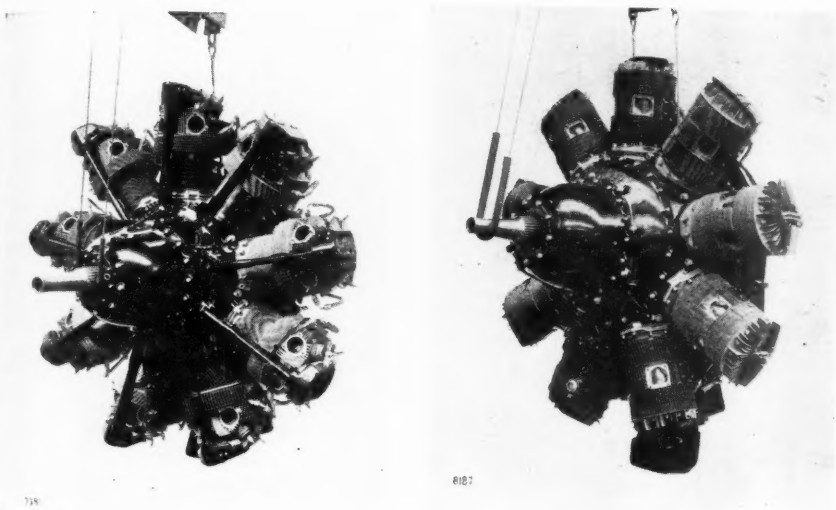


FIG. 25.
Bristol 9-cyl. air-cooled radials: Mercury poppet valve, and Perseus sleeve valve.

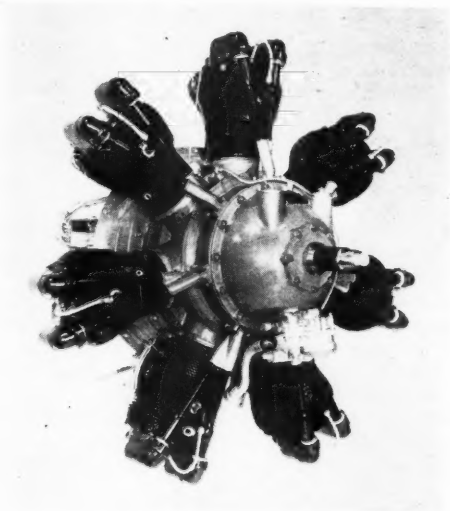


FIG. 26.
Armstrong Siddeley Cheetah 395 h.p. air-cooled 7-cyl. Radial.

Armstrong Siddeley produced three 14-cylinder two bank radial types, viz., the Jaguar of 460 h.p., the Panther of 750 h.p. and the Tiger of 935 h.p., in addition to several famous seven-cylinder types for training and Air Transport. Of these the Lynx of 240 h.p. and the Cheetah of 395 h.p. are, perhaps, the most noteworthy, the latter being illustrated in Fig. 26.

In France, Hispano, Lorraine and Salmson produced air-cooled types, and the Gnome Le Rhone Company, which held a major share of aero engine business in France with Bristol engines built under licence, produced a modified series of air-cooled radials of their own design.

From the highly successful nine-cylinder types, both Wright and Pratt and Whitney in America went on to design 14-cylinder double bank radials, for both military and civil use, and these have proved to be classic types.

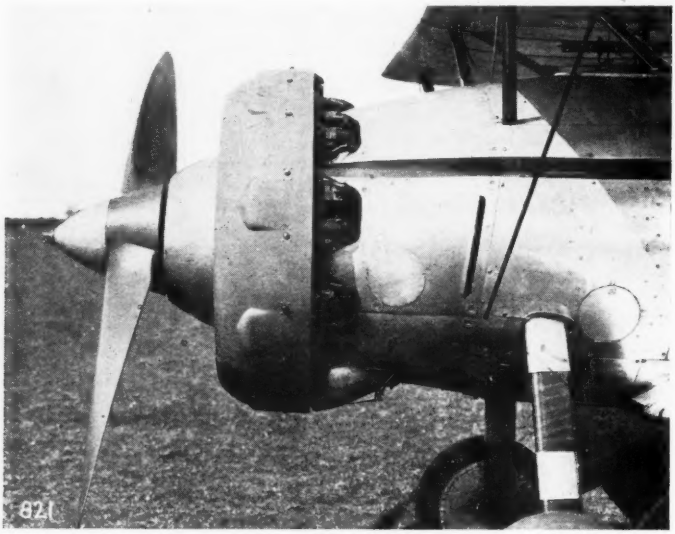


FIG. 27.
Original Short Chord Townend Ring on Bristol Mercury, 1928.

A milestone in the history of air-cooled radial engine development was reached in 1927, when the late Mr. H. Townend, of the National Physical Laboratory, discovered that such engines could be greatly improved aerodynamically by enclosing them within a circular cowl. Prior to this, air-cooled engines had usually been installed without any form of enclosing cowling. The Townend Ring might be said to have given the air-cooled radial an entirely new lease of life, for, by reducing drag greatly, it actually resulted in certain radial engined aircraft attaining higher speeds than prevailed with comparable liquid-cooled installations of the same period. Later this work was taken considerably farther in the wind tunnels of the N.A.C.A. at Langley Field, in America, and a more advanced technique, which has had a revolutionary effect on air-cooled engine installation, was evolved. A short chord Townend Ring in position on a Mercury engine is shown in Fig. 27, while Fig. 28 shows the N.A.C.A. cowling on which the first full scale tests were carried out in 1933, and Fig. 29 a later type.

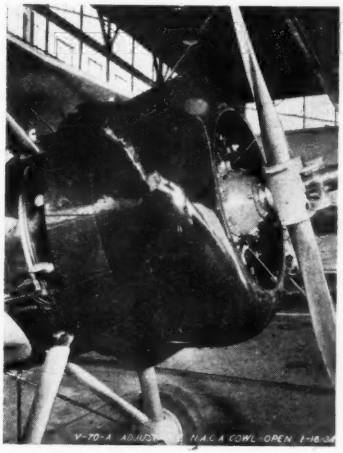


FIG. 28.

The N.A.C.A. cowling with controllable gills, on which the first full scale tests were carried out in 1933, Wright Cyclone.

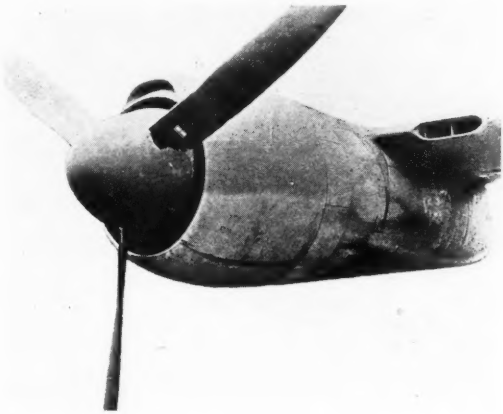


FIG. 29.

Modern type N.A.C.A. cowling.

By 1931 the urge for re-armament began to be felt once more throughout the world, and with the realisation that aircraft must necessarily play an important part in any future military operations, a fresh impetus was given to development. This, in turn, encouraged the suppliers of high grade steels and light alloys for aircraft work to intensify their own development work, not only for the direct business accruing, but also because such work had its value for application in other fields. The development of materials will be dealt with later in this paper, but it might be noted here that without this work we could never have reached the advanced technical state which we know to-day.

The changed outlook soon saw all the major countries tackling aero engine development with renewed vigour, and many others with smaller facilities for research and design were building engines under licence, mostly Bristol or American air-cooled radials. By this time Russia had come into the picture and in that country large technical bureaux were set up, and large plants were established for aero engine production, firstly under licence, but later for their own designs.

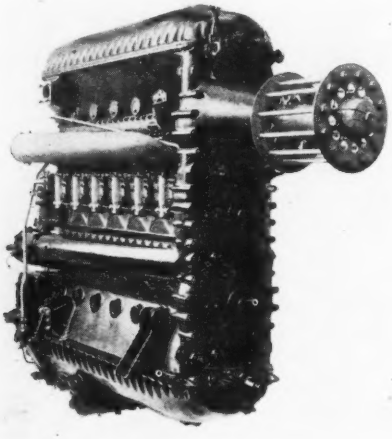


FIG. 30.

Napier Culverin 720 h.p. opposed Piston Diesel (Junkers Licence).

Shortly after this, Germany threw off the shackles of the Versailles Treaty and launched a new programme of aero engine design and development. Large sums of money were spent on the Junkers Jumo opposed piston two-stroke compression ignition engine, and considerable numbers of these were produced, probably more with the object of gaining production experience than of serious operation. A licence for this engine was taken out by the Napier Company who continued development work on their own lines. Known as the Culverin, this engine, which is shown in Fig. 30, carried out successful flight trials in a Blackburn Iris flying boat in 1934, but was dropped in view of the outstanding advances then being made in the development of the normal petrol engine. It was rated at 720 h.p. and had a specific weight of 2.48 lb./b.h.p. From time to time interest in the compression ignition engine for aircraft work has been taken by a number of constructors, but little serious development has been undertaken, since the introduction of new fuels has always given the petrol engine the advantage. Valuable work has been done in America on the Packard and Guiberson radial types, while in this country Rolls Royce carried out early experiments with a modified Condor, and Bristol produced the Phœnix, a modified Pegasus which was flown very successfully and created a World Altitude Record for C.I. engines. The rear of this engine is shown in Fig. 31.

Concurrently with the Jumo, two conventional petrol engines were put in hand in Germany, both of V.12 layout and liquid-cooled. These were undertaken by Mercedes-Benz and Junkers respectively, and tremendous drive and energy was put behind them between the birth of the present regime and the outbreak of the

second world war. Both were typically Germanic in layout, and followed out the same thesis as during the last war by being designed with a swept volume some 25 per cent. greater than for contemporary comparable types in other countries, together with moderate M.E.P.s and rotational speed.

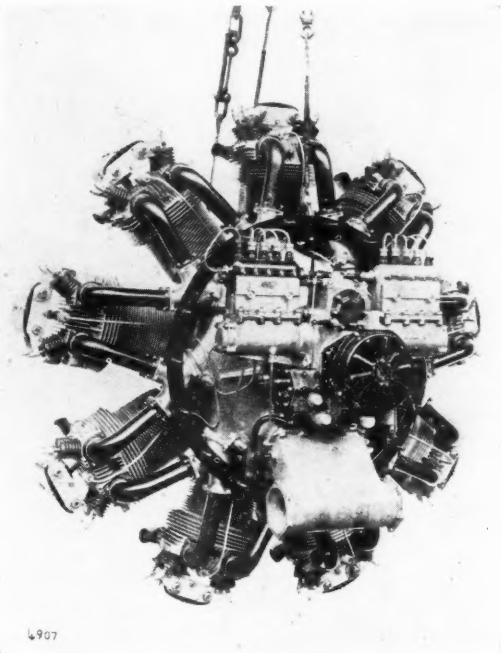


FIG. 31.
Bristol Phœnix 9-cyl. radial, Diesel 485 h.p., 1933.

In an attempt to combine the advantages of lightness and simplicity inherent in air-cooled installations with the low frontal area of the liquid-cooled type, some engine designers turned their attention to in-line air-cooled engines. An interesting specimen of this technique in this country was the Napier Rapier of 16 cylinders arranged in H form, with two independent crankshafts geared together, and which was produced in 1932 with a power of 355 h.p. This engine, which is shown in Fig. 32, was followed by the Dagger of 1,000 h.p., which adopted the same layout but had 24 cylinders in four banks of six. Air cooling has proved ideal for the lighter types of in-line engine, and we have seen how, in this country, the outstanding range of de Havilland engines—the Gipsy, Gipsy Six and Gipsy Twelve (shown in Fig. 33)—together with the Cirrus, have almost completely " scooped the pool " for light aircraft and certain civil transport types. Similar types of engine have been produced in large numbers all over the world.

Between the early 1930's and the outbreak of the Second World War, there was consistent development and the average powers available, from both air and liquid-cooled engines in all countries, advanced to the 1,100 h.p. mark, or some three times as great as those prevailing in 1918. The liquid-cooled engine

made outstanding progress in this direction and became firmly established. The outstanding development of the Rolls Royce Kestrel, Peregrine and Merlin in this country provides the most noteworthy example, and, in their re-armament programme, the Germans concentrated on the same type. The Russians, too, pinned most of their faith on to similar engines; while, on the other hand, the Japanese concentrated on air-cooled types. Despite the advances made in liquid-cooled engines, however, the air-cooled radial was still predominant in numbers,

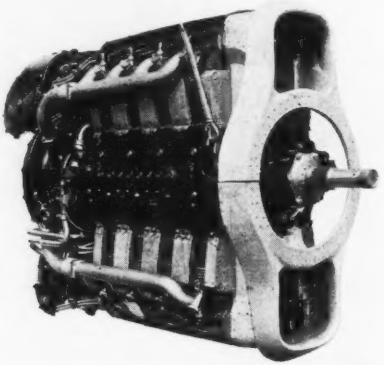


FIG. 32.
Napier Rapier 355 *h.p.* 16-*cyl. air-cooled H type,* 1932.

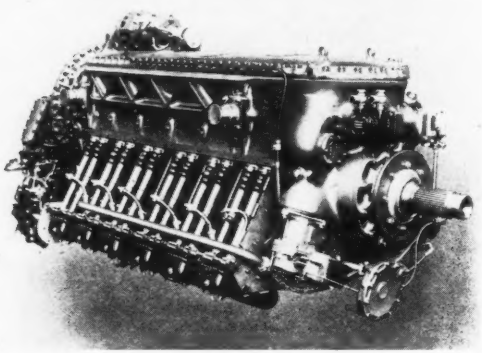


FIG. 33.
De Havilland Gipsy 12-*cyl. inverted V. air-cooled,* 1938.

largely due to American influence, although it has been said that in this country also something like 55 per cent. of the military engines being produced at the outbreak of war were of this type.

It is interesting to reflect that, at the start of this war, the two basic types in general use were the liquid-cooled V.12 and the air-cooled nine-cylinder radial, both of which were in existence at the end of the last war. No startling develop-

ments in layout had, in fact, come to fruition in the twenty years under review, in spite of the number of most interesting unconventional designs which were tested out in many countries, and progress had been rather in the direction of detail improvements in technique and the addition of refinements which, unfortunately, brought greater complexity in their train. The addition of such items as reduction gears, variable pitch propellers, superchargers, and complex carburettors for altitude operation, led inevitably to the development of specialised variants of different types of engine for specific purposes, and it ceased to be possible to use any one basic type universally.

In this hurried review of the trend of progress during those hazardous twenty years between the two wars, it has been possible to do no more than touch lightly on the remarkable progress achieved, without making any detailed examination of the technical advancement of individual components, the development of materials and fuels, or the introduction of devices to improve reliability of operation, etc. The subject is worthy of an entirely separate review of greater magnitude than is appropriate here, although some aspects will be dealt with at greater length later in the paper, but perhaps one or two points of detail might be selected for special consideration.

In liquid-cooled engines, separate steel cylinders were generally abandoned in favour of monobloc light alloy castings with wet liners, although in America the Allison engine monobloc is still flexible. At the outbreak of the present war the monoblocs in use were still not entirely satisfactory, and Glycol cooling, which had become standard practice, showed up certain defects which were only overcome by the spur of intensive wartime quantity production.

The thermodynamic performance of the combustion chamber showed enormous improvement, and the help given by the material specialists in this connection, towards the achievement of higher powers, should be appreciated. In 1920 valves could be burnt out very quickly at the highest M.E.P.s. High chrome nickel steels, sponsored by Sheffield steel makers, however, together with the introduction of sodium cooling of exhaust valves and stellite valve seatings, changed the situation beyond all recognition.

In the light alloys field also, considerable strides were made. Forged pistons, cylinder heads and crankcases were all developed and first brought into regular production in this country, and these developments were all subsequently made use of in American radials.

A further noteworthy improvement, which should be mentioned as one of great importance in the period between the two wars, was the steady development of ignition equipment, in the form of better magnetos and more robust sparking plugs. The ignition system has always been a source of trouble on the petrol engine, but although there is still room for improvement along lines which will be touched on later in this paper, great strides have been made.

No review of this period can be complete without a reference to the development which, more than any other, has enabled the aero engine to achieve the outstanding performance which it now gives, viz., the supercharger. The need for finding means of operating aircraft at elevated altitudes was recognised as far back as the last war, and in 1915 experimental investigations were made at Farnborough on piston and displacement blowers, but these were soon discarded in favour of exhaust turbo. Ellor was in charge of these original investigations on the turbo, which were first made in collaboration with Metropolitan Vickers, and a design was actually in existence, when it was learned that Rateau, in France, was working on the same lines and was actually somewhat ahead of Farnborough. In the autumn of 1918 a Rateau installation was actually flown at Farnborough in conjunction with the R.A.F. 4D engine, and a photograph of the machine is shown in Section 10 of this paper. Further developments took place after the war, and a considerable number of flight tests were carried out on a British design of exhaust turbo, first with a Liberty in a D.H. installation

and later with a Napier Lion, also in a D.H. installation. Somewhere about 1920 this latter machine exceeded 30,000 ft. The R.A.E. exhaust turbo was also designed into the Bristol Jupiter, and Fig. 34 shows a view of this arrangement. This was flown successfully for some fifty hours at Farnborough in 1924, and, with a rated altitude of 23,000 ft., an increase in speed of the order of 50 miles per hour was realised.

Unfortunately this method of supercharging was allowed to die away both in this country and France in the early 1920's, and credit must be given to Dr. Moss, of the General Electric Company, and his associates, in collaboration with Wright Field, who pertinaciously stuck to this principle and finally evolved the design which has been so valuable in giving us high altitude American bombers during the present war.

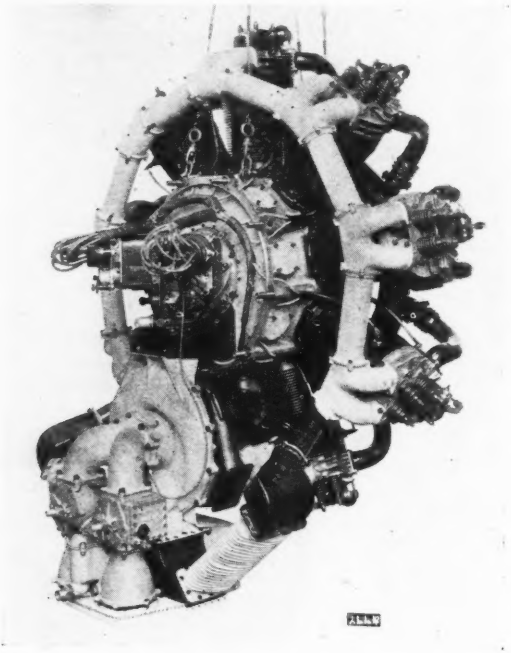


FIG. 34.
Rear view of Bristol Jupiter with R.A.E. type exhaust turbo, 1923.

To the R.A.E. must be given the full credit for the initiation and design of the gear driven centrifugal supercharger. A very successful design was developed at the end of the war, which has been a classic and has laid the foundation for gear driven superchargers all over the world. The first supercharged engine to go into service anywhere was the Armstrong Siddeley Jaguar 4S, which was fitted to the Armstrong Whitworth Siskin 3A fighter in 1926, while the first to go into large series production was the Bristol Jupiter VII in 1927, this engine, which is shown in Fig. 35, having a rated altitude of 12,000 feet. In both cases the supercharger was of the mechanically driven type based on R.A.E. designs, and from this date onwards this feature of high performance engines became

firmly established. No major change in principle was made for the next ten years or so, but with the increasing need for still higher operating altitudes, and the introduction of fuels permitting higher induction pressures, it became clear that some form of variable supercharger was required to ensure efficient operation for take-off and climb. This resulted in the development of two-speed mechanically driven types, first in France, and later in this country, taking French designs as a basis. In 1936 the Armstrong Siddeley Tiger appeared with a supercharger of this type, followed by the Bristol Pegasus XVIII in 1937, and later by the Merlin X and Pratt and Whitney and Wright types. Such superchargers are now in universal use in this war.

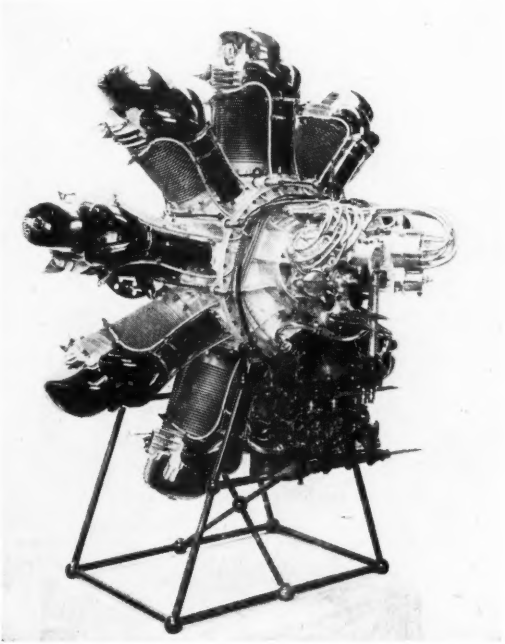


FIG. 35.
Jupiter VII Series Production type, 12,000 ft. Rating, 1927.

Two stage superchargers, the logical development for even higher altitude operation, did not reach fruition during the period under review, but the special unit of this type produced by the Bristol Company in this country in 1937, with which a World Altitude record of 59,937 feet was established, will be remembered.

One other major development which, although being dealt with more fully later in this paper, is applicable to this period, is the self-contained power plant, and a brief review of the early history of its introduction is appropriate here. The provision of quickly detachable self-contained power plants has exercised the minds of designers for many years, but it was not until the present war that the advantages of such a system were sufficiently realised to bring units into full-scale operation. Probably the first practical application of the idea was by Boulton and Paul, who exhibited a hinged power plant at the Paris Show in 1919,

and their family of twin-engined bombers, Bugle, Sidestrand and Overstrand, all employed swinging and quickly detachable mountings, although the advantages of these were not appreciated in official circles, and full use of them was not made. Another example was the Bristol Jupiter hinged power plant, which was fitted to the Bristol 10-seater civil transport aircraft in 1924, a machine which was operated on the London to Paris route for some years. In this arrangement, which is shown in Fig. 36, the engine, with all necessary accessories, was attached to a four point mounting designed to fit on four pick-up points on the aircraft bulkhead, in such a manner that the power plant could be hinged sideways on two of the pick-up points for immediate inspection and maintenance.

FIG. 36.
Jupiter swinging mounting on Bristol Transport, 1924.

About 1929 Rolls Royce, having become impressed with the importance of a satisfactory installation to the functioning of the engine itself, decided to set up a special department for carrying out development work and, as a result, to be in a position to advise customers on the best installation arrangements to be adopted. In their Aero Catalogues of around this date, proposed layouts were shown, and these were, as a rule, closely followed by aircraft constructors. As the power of engines increased, the installational difficulties became more severe, and, in consequence, in 1935 Rolls Royce found it necessary to set up a detached establishment devoted entirely to the flight testing of engines and their installations. This led directly to the construction by the engine builder of complete power plants. In the initial stages such power plants were built with

the object of demonstrating in a practical way the best methods of using Rolls Royce engines so that the aircraft constructor might benefit. As time went on, it became increasingly clear to aircraft constructors that, not only the design and development of the power plant, but also its manufacture could best be left in the hands of the engine builder.

Towards the end of 1937, the Air Ministry approached the Society of British Aircraft Constructors and asked them to prepare a scheme whereby engines of similar horse-power, but of different types, could be interchangeable in certain classes of airframe at no more than 48 hours' notice at aircraft constructors' works. A special Committee was set up by the S.B.A.C., and within six months a report was submitted to the Air Ministry which showed that the scheme was quite practicable.

For one reason and another, mainly due to the exigencies of war expansion, it was not found possible to give effect to the S.B.A.C.'s recommendations. The work of the Committee was, however, by no means wasted as it provided an excellent opportunity for an exchange of views between engine builders on the design and supply of self-contained quickly detachable power plants and, also, it did much to impress aircraft constructors with the advisability of entrusting engine builders with the supply of complete power plants, thus saving them from one of the most frequent causes of delay and worry in the development of new types of aircraft.

To sum up this very sketchy survey, it might be said that the twenty year period between 1919 and 1939 was one during which the emphasis was on major improvements to established basic engine types, rather than on the introduction of really novel layouts, although a great variety of different types were tried out in experimental form. The groundwork was laid, however, for a number of important changes which came into prominence at the beginning of the present war. and these will receive fuller consideration in the next section of this review.

Section 5.—Present Engines and Power Plant.

For security reasons, the history of the progress of the aero engine during this war cannot be told yet, and it is only possible to skim over the many developments which have been made by the United Nations and the Axis powers, during the period from 1939 to the present time.

The war started with all the major countries having engines of about the same power, viz., 800 to 1,100 h.p. The progress that has been made since 1939 can be seen from Fig. 37, which gives the latest available published powers of some of the more important engines which are in widespread use by the belligerents, and it will be seen that the power output of the latest large engines is already double the figure for 1939.

It will be noted that the products of some of the belligerents have been omitted. Owing to the fall of France in 1940, and the resulting limitation of operation of French aircraft, it has not been thought worth while to include their engines. The Italians used their own engines in the first instance, but owing to certain difficulties, including the supply of raw materials, they turned their production over to the manufacture of German types before they passed out of the war. It has been practically impossible to obtain data on Russian and Japanese engines, with the exception of the 14-cylinder air-cooled radial used in the Zero fighter, details of which have been published in the Technical Press, via America. These show that this engine is very typical of the Pratt and Whitney school of thought.

Judged by the tempo of development, it is believed that it will be found that we shall finish the war with very nearly the same step up in power over the present war period as occurred between 1914 and 1918, viz., an average increase of about three times, and that this war will probably end with engines of over 2,500 h.p.

TABULATION OF LEADING ENGINES OF ALL BELLIGERENTS.

PRESENT WAR.

AIR-COOLED RADIALS.

Name and Type.	Country.	No of Cyls.	Bore and Stroke.	Swept Vol. Litres.	Present Published Operational Power.
Bristol Mercury .	Britain	9	5.75×6.5	24.9	955
Bristol Perseus .	,,	9	5.75×6.5	24.9	935
Bristol Pegasus .	,,	9	5.75×7.5	28.7	1000
Wright Cyclone .	U.S.A.	9	6.125×6.875	29.9	1200
B.M.W. 132K. .	Germany	9	6.125×6.375	27.7	960
Bristol Taurus .	Britain	14	5.0×5.625	25.4	1130
Bristol Hercules .	,,	14	5.75×6.5	38.7	1650
P. & W.R. 1830 .	U.S.A.	14	5.5×5.5	30.0	1250
Wright G.R. 2600.	,,	14	6.125×6.312	42.7	1700
B.M.W. 801. .	Germany	14	6.15×6.15	41.9	1650
P. & W. 2800 .	U.S.A.	18	5.75×6.0	46.0	2000
Wright 3350 .	,,	18	6.125×6.312	54.9	2200
B.M.W. 3400 .	Germany	18			2500
	LIQUID-COOLED IN-LINE TYPES.				
R.R. Merlin .	Britain	12	5.4×6.0	27.0	1650
R.R. Griffon .	,,	12	6.0" Bore		1750
American Merlin .	U.S.A.	12	5.4×6.0	27.0	1520
Napier Sabre .	Britain	24	5.0×4.75	36.7	2200
Mercedes Benz 603	Germany	12	6.4×7.1	44	1700
,, ,, 603A	,,	12	6.4×7.1	44	1800
,, ,, 610	,,	24	6.06×6.3	69.8	3000
Allison V. 1710 .	U.S.A.	12	5.5×6.0	28.0	1300
,, W. 3420 .	,,	24	5.5×6.0	56.0	2200
Jumo 213 . .	Germany	12	5.9×6.5	34.2	1700

FIG. 37

The tempo of technical development and production capacity for aero engines has been intensive, and has brought out the highest skill and initiative that has ever been achieved in mechanical engineering. The aeroplane has shown itself to be a most deadly and effective weapon, and the demand for higher performance and greater altitude from a given type of engine, has been ever increasing as the war has proceeded. The production technique has been quite remarkable, and although the output figures for this country cannot be quoted it has already been stated in print that America is producing over 200,000 engines per annum, thus placing the complex precision made aero engine in both countries on a similar quantity production basis to that of the motor car, which has never previously been envisaged as a practical possibility.

When war broke out the psychology and technique of aero engine production was in a better and more advanced state than for airframes. This is because the aero engine constructors were more production minded, and had an outlook more akin to that of the motor car or precision machine tool manufacturer.

Considerable experience had been gained by the Bristol Co., in their licence manufacture all over the world, which had already taught them the method of laying out their drawings and preparing data for manufacture remote from the parent factory, and this was of the utmost help in getting going on the "Shadow" production. It is considered that due credit should be given to the Air Ministry, the Bristol Company, and to the motor car manufacturers for the far sightedness of the Shadow industry, which was initiated some three years before the outbreak of war. A similar Shadow scheme was developed somewhat

later by Rolls Royce, but in this case, direct control was retained by their own management. From their own point of view this was probably a better course, as it enabled improved types of engines to be introduced into production more quickly.

Undoubtedly, their advanced psychology on their own production, and their experience of having planned everything well ahead for their material and accessory suppliers in a cut and dried form, enabled British aero engine manufacturers to go forward with the scale of wartime production more quickly and smoothly than airframe makers. The accumulated experience of the British Industry enabled engines always to keep ahead of airframes, and, practically speaking, at no time in the war has there been any shortage of engines.

Great ingenuity and large sums of money have been spent on tooling and special purpose equipment, and the production achievements for aero engines in this country have been outstanding. It is difficult to quote accurate figures for man hours per b.h.p. of the engines being manufactured, but it would appear that both in this country and in America, air-cooled radials are being produced at 1.4 man hours per b.h.p., and certain liquid-cooled in-line types for only a little more. There has been close collaboration with the Machine Tool Industry and several interesting special purpose machines have been produced for aero engine manufacture. Figs. 38 and 39 show representative examples, the first being the Drummond Maxicut special lathe for turning fins on the Hercules cylinder, and the second the Archdale 36 spindle machine for drilling and reaming Rolls Royce crankcases. The Maxicut completes the whole fin cutting operation in six minutes, cutting 52 fins with 104 tools, and removing 20 lb. of metal in the process.

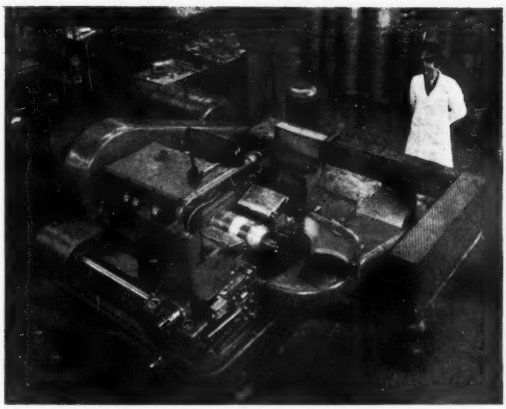


FIG. 38.
Special Drummond Maxicut Lathe for finning Hercules cylinders.

Most extensive equipment for pattern making, die casting, and the rapid forging of light alloy aero engine parts has gone ahead in an equally remarkable way, and the centrifugal casting technique for high expansion ferrous material for sleeves has made the sleeve valve engine possible, although there is still considerable scope for improving manufacture of these parts. Considerable studies have been made in the drop-stamping, heat treatment and hardening of all classes of alloy steel stampings for aero engines, and a variety of organisations previously unversed in this work have been drawn to assist.

Aero engine Shadow production factories like those of Bristol and Rolls Royce in Britain and of Wright Aeronautical in America have an assemblage of machine tools, jigs and fixtures of a finer and more comprehensive nature than has ever been collected together before for any one single type of precision series manufacture, and the cost of the equipment at each of these plants has run into many millions of pounds.

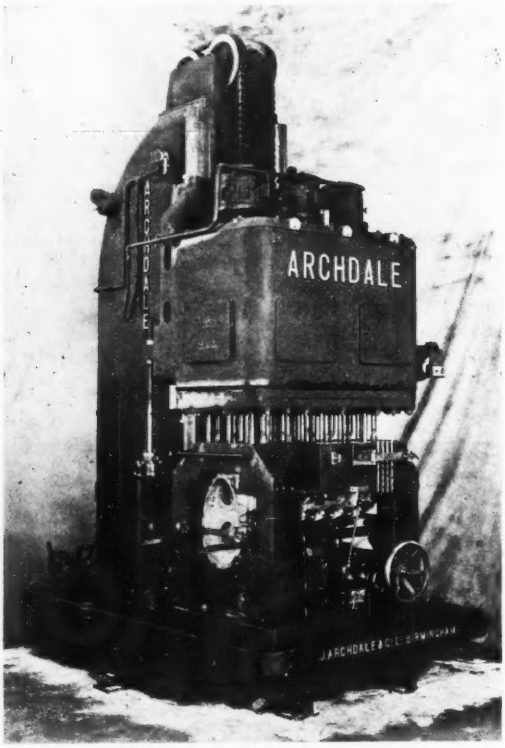


FIG. 39.

Special Archdale 36 spindle drill Press for Rolls Royce crankcases.

The war, and the consequent urge for production has prevented revolutionary developments coming in during this period. Perhaps the most interesting single production problem, which has been tackled and standardised, is that of the sleeve valve used on the Bristol Hercules and Napier Sabre, both of which have been brought to production fruition during war time, while the most outstanding development of any one particular engine or firm, is probably that of Rolls Royce on their Merlin, the power output of which has been nearly doubled and the rated altitude nearly trebled. This has been done mainly by ingenious and painstaking development of the supercharger, and this engine has made a great contribution to the war effort.

In the sphere of air-cooled radials, Britain, America and Germany have all made considerable progress. In Britain, the Bristol Mercury was chosen for

the 1936 " Shadow " production scheme, and in 1939 new " Shadow " facilities were created for the sleeve valve Hercules. Bristol engines in service have continued to use mechanically driven single stage single speed or two-speed superchargers and the progressive increases in rated altitude have been considerable. The new Bristol Centaurus 18-cylinder radial of over 2,000 h.p., incorporating many improvements as a result of experience on Hercules, should prove a worthy successor to the latter engine.

The American air-cooled radials which built up such an enviable reputation before the war for civil work, were not at the outset in all cases altogether suitable for military purposes; some trouble was experienced with overheating and lack of power at altitude on some of the early American types, but these faults have been put right and the engines are now doing magnificent work in all theatres of the war. The outstanding high power American engine at present in large series production is the 18-cylinder 2,000 h.p. Pratt and Whitney air-cooled Radial. This is a highly developed and reliable type, and it has built

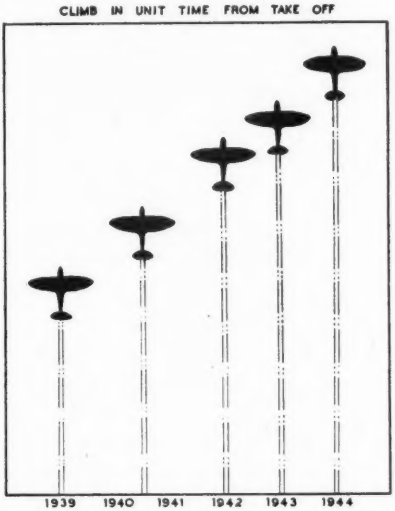


FIG. 40.

up a most enviable reputation in all theatres of the war. Great credit is due to the Americans for the application of the G.E.C. exhaust turbo to the Fortress and Liberator, as this has permitted their bombers to go regularly over enemy country in daylight at altitudes in excess of 25,000 ft. The Pratt and Whitney Company have produced successful two stage mechanical supercharger types in full series production, but their rated altitude does not compare favourably with that of the Merlin two stage series.

Although Germany, when she initiated her expansion programme in 1934, concentrated first on the two-stroke Diesel, and later, shortly before war, on the inverted V.12 liquid-cooled engine with fuel injection, radials were at no time completely abandoned, and a spectacular " come-back " was apparent with the introduction of the F.W. 190 early in 1942 with a 14-cylinder B.M.W. air-cooled radial of somewhat larger capacity than the Bristol Hercules. Although

the power output of this engine was in no way remarkable, the installation was ahead of anything else at the time, and the excellent automatic control system on this power plant has pointed the way for the future.

Amongst the high power air-cooled Radials of this war, it is considered that the Pratt and Whitney R. 2,800 and the Bristol Hercules are making the greatest contribution to the war effort.

In the realm of liquid-cooled in-line engines, the Rolls Royce Merlin is in a class by itself, but this superiority has been achieved only by the most careful development by an enthusiastic team. The Rolls Royce development of the two-stage mechanically driven blower with after-cooler has been an outstanding contribution to the success of our latest fighters, and Fig. 40 gives some indication of the progressive improvement in the climb of the Spitfire which has been made possible.

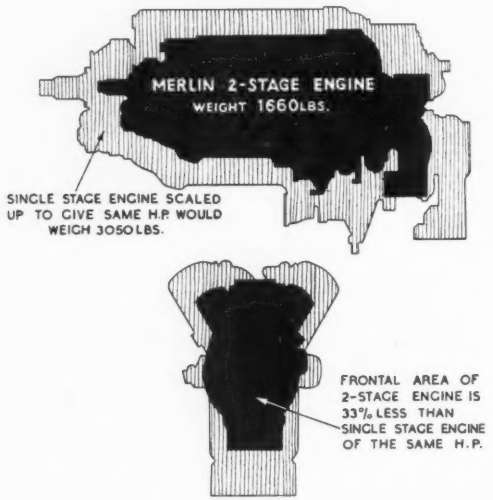

MERLIN 2-STAGE ENGINE
WEIGHT 1660LBS.
SINGLE STAGE ENGINE SCALED UP TO GIVE SAME H.P. WOULD WEIGH 3050LBS.
FRONTAL AREA OF 2-STAGE ENGINE IS 33% LESS THAN SINGLE STAGE ENGINE OF THE SAME H.P.

DIAGRAM SHOWING SAVING IN SIZE AND WEIGHT
ACHIEVED BY ADOPTION OF
TWO-STAGE SUPERCHARGER & INTERCOOLER

BOTH ENGINES WOULD GIVE SAME POWER AT 30,000 FT.

FIG. 41.

The Napier Sabre is the first liquid-cooled sleeve valve engine to come into series production, and this engine, with its 24-cylinder H layout has recently been fully described in the Press. To introduce such an engine in wartime is, in itself, a highly creditable achievement, and a classic layout which will point the way to further new engines of similar design in the future has been initiated.

The Americans have specialised on air-cooled radials, and their only large scale production liquid-cooled in-line engine—the V.12 Allison—is not outstanding in specific output. It has, however, the distinction of being the one production engine of the war which is successfully operating with an extended shaft drive. The new 24-cylinder Allison, comprising two V.12 engines in W formation on a common crankcase, and which was exhibited at the New York World Fair in 1939, is probably one of the most powerful engines in production at the present

time. The Rolls Royce Merlin is being manufactured in large quantities by the Packard and Continental Engine Companies.

The Germans attacked the problem of the in-line liquid-cooled engine with great thoroughness, but with a completely different line of approach. As in the last war, their thesis has been to use a large engine running at low boost and low piston speed, and their increase of 7 litres over the Merlin gave them an advantage in the early days of the war, at which time the power-weight ratio of the Mercedes-Benz DB. 601 engine was superior to that of the Merlin. This

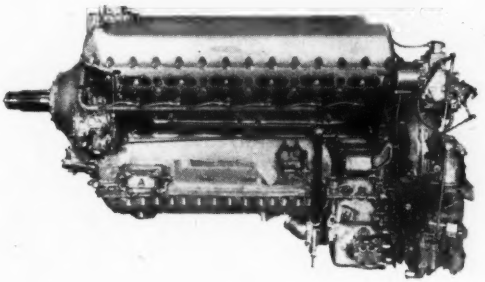


FIG. 42.
Rolls Royce Griffon 1,750 h.p. liquid-cooled 12-cyl. V., 1944.

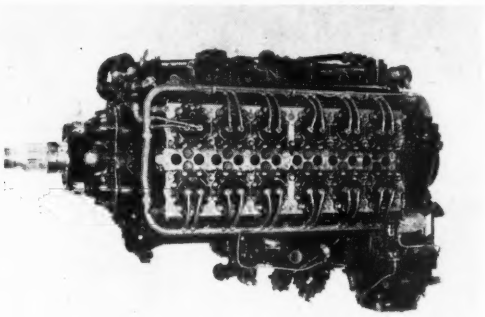


FIG. 43.
Napier Sabre 2,200 h.p. liquid-cooled 24-cyl. H., 1943.

was soon changed by the introduction of the improved single stage Merlin blowers, while the latest two-stage supercharged Merlin engines now show a material advantage over and above the latest German types of even larger swept volume. It is impossible, in fact, to obtain the best performance at high altitude merely by using an oversized engine and maintaining a low boost to great height, and this is well illustrated by Fig. 41, which shows the saving in weight and

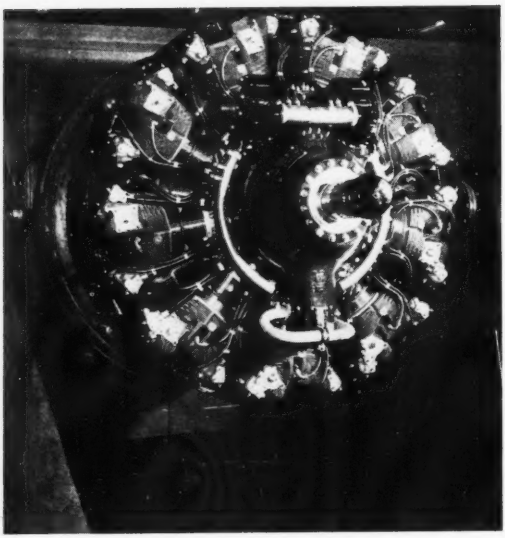


FIG. 44.
Wright Duplex Cyclone 2,200 h.p. air-cooled 18-cyl. 2 Bank Radial, 1944.

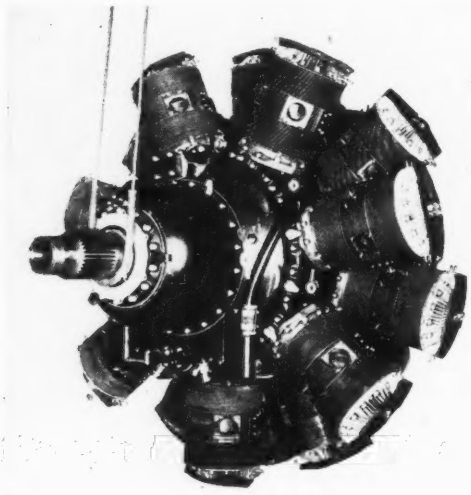


FIG. 45.
Bristol Hercules, 1,650 h.p. air-cooled 14-cyl. 2 Bank Radial, 1943.

frontal area which has been achieved by the two-stage Merlin, compared with a similar single stage engine scaled up to give the same power at 30,000 ft.

It is interesting to note that the Mercedes-Benz DB. 601 and the Junkers Jumo had the same cylinder bore—5.9 in.—although the latter engine has a stroke 0.2 in. longer at 6.5 in. The latest Mercedes-Benz has retained the 6.3 in. stroke, but the bore has been increased to 6.06 which makes its bore and stroke identical with those of the Bramo Fafnir nine-cylinder radial.

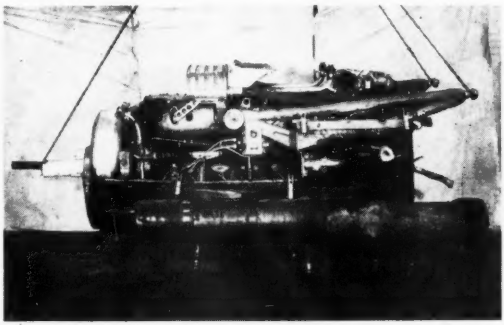


FIG. 46.

Mercedes-Benz 603A 1,800 h.p. liquid-cooled 12-cyl. inverted V., 1944.

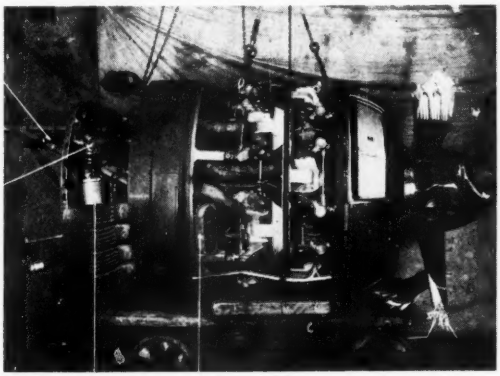


FIG. 47.

B.M.W.-801 1,650 h.p. air-cooled 14-cyl. 2 Bank Radial, 1943.

Mercedes-Benz have produced a 3,000 h.p. unit by gearing two DB. 601 engines together into a complete power unit for large bombers. We do not know a great deal about this combination, but it is understood that some trouble has been experienced with the gearing, and it would seem that some form of hydraulic coupling is necessary. There has also been a good deal of trouble with fire in the nacelle, and the whole layout does not seem to have been a very happy one.

It is considered that the two most important improvements in aero engine component assemblies during the war have been the continual increments of

blower efficiency and the introduction of improved fuel distribution schemes. England has certainly led in the former with the Merlin, while direct petrol injection has been a monopoly of Germany up to the present time, although injection carburettors are now standardised on both American and British engines.

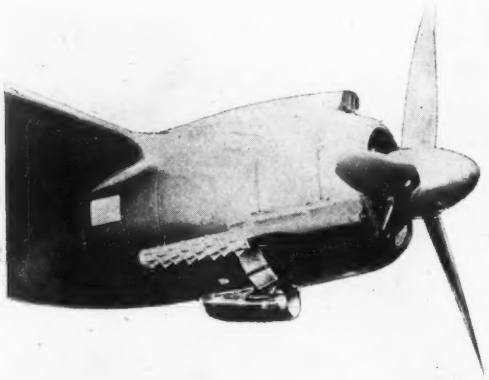


FIG. 48.
Hercules Power Plant in Halifax.

FIG. 49.
Merlin Power Plant in Lancaster.

Fig. 42 shows the Rolls Royce Griffon and Fig. 43 the Napier Sabre, representative of the latest British liquid-cooled engines, while Fig. 44 shows the Wright 18-cylinder, and Fig. 45 the Bristol Hercules, representative of the latest highest power Allied air-cooled engines. Fig. 46 shows the latest example of the German Mercedes-Benz inverted V.12, and Fig. 47 the 14-cylinder B.M.W.801, both with fuel injection.

Considerable advances have been made in quickly detachable power plants during the war period. By 1939, Bristol and Rolls Royce were both well estab-

lished as builders of complete power plants. Bristol had an initial advantage in that the Hercules was provided with an auxiliary gearbox, and they were therefore able to approach the ideal of a universal power plant. Owing to the limitations imposed by the absence of an auxiliary gearbox drive on the Merlin, it was only possible to provide a basic power plant, and specialised addenda had to be provided for each particular application. This made completed power plants positional and not universal.

The advantages of the standard power plant are clearly shown by the illustrations of Bristol and Rolls Royce installations, shown in Figs. 48 and 49. The first shows the Bristol Hercules power plant installed in the Halifax, while the second shows the Rolls Royce Merlin power plant installed in the Lancaster.

Although some small thin winged machines like the Mosquito have departed from the standard power plant by adopting wing radiators, it is doubtful whether any appreciable performance advantage can be shown, and it is not believed that it is worth abandoning the standardised power plant unless the ducting is extremely carefully carried out, and the internal drag reduced to a minimum.

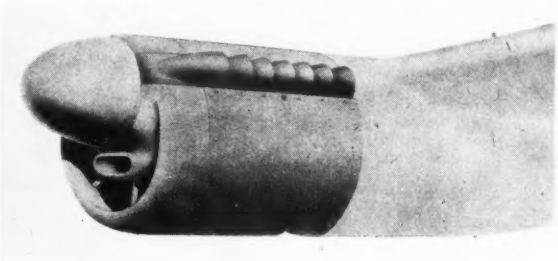


FIG. 50.
Latest Merlin circular Power Plant, 1944.

The two-stage Merlin and the Griffon are now both produced with an auxiliary gearbox drive, and this has allowed these engines to be supplied as universal power plants of clean design, which can be applied in any position on a variety of different types of multi-engined aircraft. The latest Rolls Royce power plant illustrated in Fig. 50 is of cylindrical form. Liquid-cooled engines had already been installed in power plants of this shape in Germany, so as to render them interchangeable with air-cooled installations, and they offer advantages in looking after the requirements of armouring and maintenance, and also the provision of flame damping by a ducted outlet of the radiator exit air. As a measure of the progress that has been made, power plants could now be supplied to go on the same aircraft, without modifications, incorporating either the Merlin or the Griffon.

Bristol have also advanced their power plant design, and, like Rolls Royce, have gone quite a long way towards making the whole installation a better engineering job. As will be seen from Fig. 51, which depicts one of their later Hercules power plants, the exterior has now been made much cleaner. Other improvements in this power plant are an improved exhaust system and more efficient flame damping.

To the student of Internal Combustion Engineering, this war has seen a stupendous effort by all the belligerents towards the intensive technical development and the production on an unprecedented scale of a series of liquid-cooled in-line and air-cooled radial aero engines, such as have never been contemplated before. This great achievement has only been made possible by outstanding

team work in all the different countries concerned. There is something about aircraft power plant engineering which is unique, and once having been bitten by the absorbing interest of its technique, the engineer seldom relinquishes it. I think this is chiefly due to the fact that since one is always striving after something better, and the opportunity is given to use the best materials and workmanship, this breeds enthusiasm and drive, two vital qualities necessary for success.

Be that as it may, there has been the most remarkable team work in this country on Aero Engine Production. It has entailed drawing in a comprehensive range of productive trades, including the motor car industry, and the suppliers of fabricated materials, accessories and precision machine tools, and all have contributed their full share in a most collaborative spirit. The same can be said of the great American industries also. This country can be proud of the

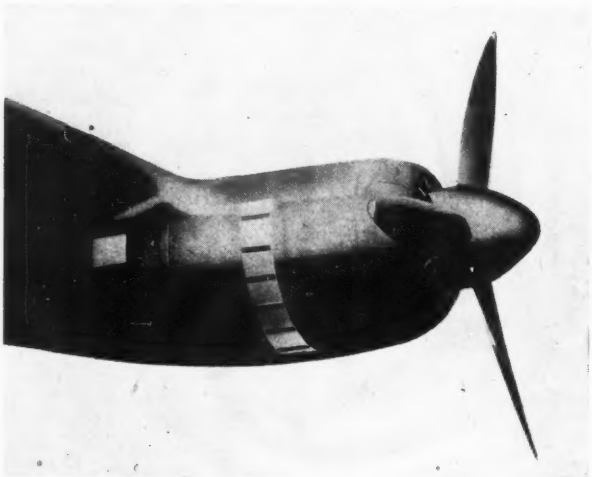


FIG. 51.
Latest Hercules Power Plant, 1944.

effort, and the resulting remarkable range of most efficient military engines. From these, and with the experience derived from their design, manufacture and operation, we must be ready after the war rapidly to build up an even better family of prime movers for Civil Air Transport.

SECTION 6.—FUELS AND LUBRICATING OILS FOR THE FUTURE.

Previous reference has been made in this paper to the effects of improved fuels on the development of high output aero engines, but the whole question of the future of the piston engine is so closely governed by the quality of the fuels and lubricating oils, which may become available, that it is only right that a separate section should be devoted to a broad survey of past, present and future possible trends in the development of petroleum products.

Without the willing co-operation of the fuel technologists and their continuous efforts to provide the high quality fuels which are available to-day, the history of aviation engine development might have been very dull compared with the records of the remarkable achievements which have actually been realised since 1920, when serious full-scale fuel development was first commenced.

How much longer the demand for specialised research on improved fuels for the reciprocating engine will continue must depend upon the influence of gas turbine development on the useful life of the former, but it is certain that as long as there is active competition between the two types of power plant on common ground, *i.e.*, in the 1,500-6,000 h.p. range, the petroleum technologists will be pushed still harder by the piston engine protagonists in an effort by the latter to hold their own on general power plant performance, but more particularly in regard to the possible " Achilles heel " of the turbine, economy in fuel consumption.

However, before dealing with such matters in any detail, it is as well to give a brief picture of the history of fuel development.

History.

Before passing on to the era of modern fuels, and organised methods of investigation into their performance in spark ignition engines, one must refer back to the early days of the aero engine. Prior to the last war, internal combustion engineers were not fuel conscious, and were mainly concerned with obtaining motor spirits which were sufficiently volatile to ensure reasonably good admixture of the air and fuel, with the aid of the somewhat primitive carburettors which were available at that time. Petrol was specified merely by its specific gravity and particular brand.

About 1912-1914, however, in attempting to improve engine specific performance, troubles were encountered, such as abnormal overheating leading to piston failures, and there is no doubt that these were caused by detonation and/or pre-ignition, though no proper understanding of the theory of detonation as distinct from pre-ignition existed at the time. It is of interest to recall that at about that time Professor Hopkinson was engaged in some research at Cambridge into the combustion phenomena of mixtures of hydrocarbon fuels and air, having, I believe, as one of his students or co-workers H. Ricardo. It is probably not an exaggeration to suggest that this very early work of Hopkinson did much to inspire the researches into the theories and causes of detonation so ably conducted in subsequent years by Ricardo, Gibson, Tizard, Pye, Callender, Midgeley, Boyd, and many others.

About 1916, Ricardo was engaged in his now classic research into the performance of the fuel in internal combustion engines, and established that with an increase in compression ratio of the spark ignition engine, certain fuels developed a tendency to detonate in the cylinder. The extent to which this occurred was found to vary with fuels of different origin, and it was already known that the addition of aromatics such as benzole to the petrol offered considerable relief in avoiding this adverse combustion phenomenon, although they did not overcome pre-ignition.

At the conclusion of the last war, the Shell Company, recognising the importance of research into the performance of fuels undertook a programme, in co-operation with Ricardo, to study the theory, causes and effects of detonation, and also the manner in which the constituents of various hydrocarbon fuels governed the phenomena. This work led to the development by Ricardo of the first variable compression engine, subsequently known as the E-35.

As indicated, this research was not put in hand until after the last war, and therefore, during the period of hostilities, we had to use in our military machines various types of petrol, some of which were blended with benzole and other compounds, and which were found by trial and error on the part of the engine makers to give satisfactory results. Probably the anti-knock values varied between 50 and 65 octane number, although there was, of course, no method of measuring such properties at the time.

Research was also carried out in France about 1918-1919 by Chavanne and Simon, who discovered that the aniline point of petrol was an indication of its

aromatic content; this leading to the establishment of the relationship between aniline point and anti-knock properties of petroleum spirit.

Subsequently, during the period up to about 1929-1930, a considerable amount of research was carried out all over the world, and of the increase of some 30 per cent. to 40 per cent. specific power output of the aero engine realised over this period, at least 15 per cent. to 20 per cent. was directly attributable to the improvement in anti-knock quality of the fuels used.

Although Great Britain played a leading part in the pioneer work on the improvement of fuels and appreciation of their behaviour in the spark ignition engine, even greater credit must be given to America where in 1921 the work of Midgeley and Boyd, sponsored by Kettering of the General Motors Corporation, resulted in the discovery of the properties of tetra-ethyl-lead. This achievement can well be considered as one of the greatest single contributions on record towards the advancement of fuel technology, and though this compound was not

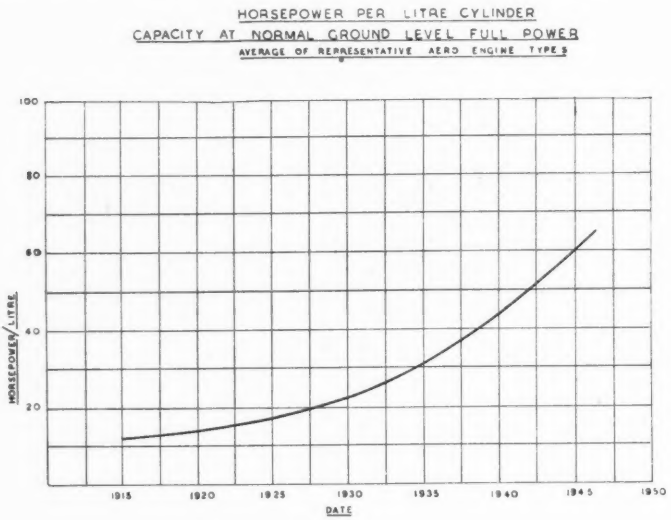


FIG. 52.

Curve showing trend of improvement of H.P./Litre,
1915-1944.

immediately accepted as a constituent of aviation fuel, its subsequent use has had, as we all know, a far reaching effect on the performance of the aero engine. Following this work the octane number scale was originated in 1925 by Dr. Graham Edgar, who observed that pure iso-octane had about the highest anti-knock value of any pure hydrocarbon at that time, while normal triptane had an extremely poor performance. As is well-known Dr. Edgar then evolved the accepted method of measuring the anti-knock quality of fuels by comparing them with a mixture of iso-octane and normal heptane, and measuring the percentage of iso-octane required in the mixture to give the same anti-knock properties of the fuel under test.

Again it must be remembered that while we were at a stage when lead addition to more or less straight run fuels had reached a maximum which the engine could stand at that time, the Americans established the production of iso-octane and similar blending agents on a commercial basis. This opened the

way to large scale production of fuels with anti-knock values in excess of 87 octane.

While such work on the fuels was in progress, the difficult problems of basic rating and correlation had to be dealt with, and the tests defined as the C.F.R. motor method and modified motor method, developed in the U.S.A. were accepted in that country and Great Britain respectively, for determining anti-knock performance at weak mixtures.

During the last ten years great strides have been made towards extending the range of blending agents and synthetic fuels for high octane ratings, and 100 octane spirit, first released for general experimental work in 1934, came into full scale military use in 1939-1940. Since then it has been produced in ever increasing quantities, and at the present time is used throughout the Allied Air Forces in almost every type of operational aircraft.

There is still ample scope and considerable promise for future improvements, however, and these matters will be touched on at a later stage in this section.

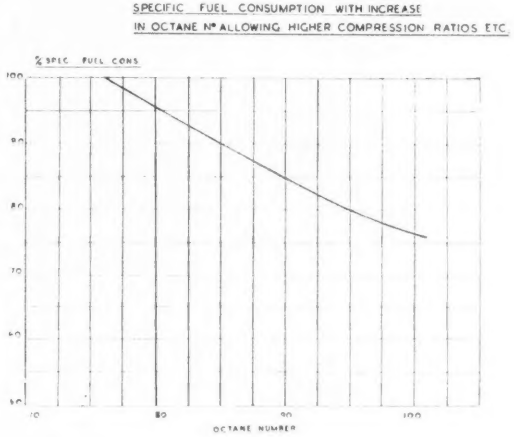


FIG. 53.

Curve showing improvement in economical cruising consumption with increase in Octane No., 1928-1944.

The following diagrams illustrate clearly the extent of the achievements made possible by the combined efforts of the fuel technologists and the aero engine designers. Fig. 52 indicates the general trend in increase of horsepower/litre from 1915-1944. Fig. 53 indicates the gradual improvement in economical fuel consumption from 1928-1944.

Specific Problems in Aero Engine Design Connected with Fuel Improvement.

As previously mentioned the first serious attempts to improve fuels involved the blending of varying percentages (10-25 per cent.) of benzole with any straight run spirits boiling in the gasoline range. When the highest possible anti-knock properties of the fuel had been achieved by this means, the main problems which confronted the aero engine designer were the provision of adequate cooling to prevent pre-ignition, and the general design of components to withstand the stresses incurred by permissible increases in B.M.E.P. Other aromatics such as toluene and xylene were used to suppress detonation, and the blending of acetone and alcohol was also employed for special racing or competition purposes.

The main disadvantages of the aromatics were their proneness to give rise to pre-ignition, and their reduction in knock rating at elevated temperatures. In addition the freezing point of benzene is about 5°C. and thus as the operating altitude of aircraft increased, the amount of benzole which could safely be blended with the petrol had to be restricted.

With the introduction of leaded fuel, in spite of its welcome properties of knock suppression, came the bitter struggle with lead attack and cold corrosion.

The exhaust valve, never a very happy component, even with straight run fuels, owing to its high operating temperature, became the victim of severe attack mainly due to the fusing of lead oxide with the surface skin of the valve head and seat. Many thousands of hours single cylinder and main engine running has been devoted to the elimination of this trouble, and at the present time, thanks to the co-operation of the metallurgist and development engineer we are able to run our poppet valve engines with relatively high lead concentrations and comparative freedom from lead attack; in fact, satisfactory short duration tests have been carried out on liquid-cooled engines with leaded fuels containing up to and even higher than 16 c.c.s./I. Gall. Even so it is probably true to state that the air-cooled poppet valve engine still has to be watched very carefully as regards lead attack, particularly under conditions of prolonged weak mixture cruising.

Another component which gave endless trouble with leaded fuel was the sparking plug, but the defects encountered were largely bound up with the use of mica as the insulating medium, and now that the sintered aluminium oxide plug insulator is used almost universally on high output aero engines, lead deposit troubles have been kept within bounds. There is still considerable room for improvement of the sparking plug, however, and every effort must be made to develop new types with higher heat ratings and improved design for use with future high octane fuels. We require for the future an entirely new conception of reliability of this component, giving absolutely trouble free operation in civil airline engines for long periods without adjustment.

The passage of lead compounds into the crankcase has given rise to a certain amount of additional sludging trouble, coupled with heavy film coating over the internal components of the engine, but otherwise seems to have no adverse effects.

Cold corrosion troubles have largely been overcome with changes in materials and surface treatments, together with the use of suitable inhibitors such as D.T.D.437 (E.G.174), although this latter has now been superseded by an improved material D.T.D.587, this consisting of an oil containing corrosion inhibiting compounds, on which, if desirable, the engine can be operated prior to shut down.

A further precaution which has proved itself well worth while, but which we have as yet made insufficient effort to adopt in this country, is the practice of enclosing engines in sealed Pliofilm, or other moisture and air-impervious envelopes. Such practice coupled with the insertion of hygroscopic chemicals such as silica-gel, inside the envelope and in suitable containers screwed into the spark plug adaptors, ensures that the engine can be transported in its packing case anywhere in the world without risk of corrosion or lead attack which may ruin the surfaces of cylinder bores, valves, rings, ball and roller bearings, etc.

Lead attack of the exhaust pipes and collector rings of air-cooled radials presented itself in the days when these components were fabricated from mild steel sheet, but again a change in material to nickel chrome steel and internal nickel plating has successfully combatted serious conditions of lead attack.

Other aspects such as the gumming of piston rings and steady increase in maximum pressures are a function of the increased power attainable with leaded fuels rather than of the fuels themselves, and discussion of such matters is outside the scope of this paper.

Future Developments.

Referring again to Fig. 52 and bearing in mind the foregoing brief review of what has been achieved over the last 30 years, we find ourselves wondering if we can keep the slope of the progress/time curve constant where the quality and availability of high performance fuels are concerned. I believe that with the necessary effort this is possible. Apart from the more immediate needs of higher power output for military requirements we must try and look into the future to see what fuels will be available for the civil airline operator.

In the case of the latter, it will be of the utmost importance if civil aviation is to prosper, and be of universal benefit to people in all walks of life, that the fuel, which represents some 15-20 per cent. of the cost of airline operation, should be produced and supplied at the lowest possible price, but at the same time should be of sufficiently high quality to allow suitably redesigned, existing military type engines to be operated when necessary at the same ratings as those for which they have been cleared for service use. This virtually means that we must continue the production of 100 octane spirit, using the minimum lead content, and ensure that it is properly distributed along all the world's commercial air routes.

In view of the well planned policy of the United Nations in ensuring, with the rapid construction of new plant, and the development of new refining processes, a plentiful supply of 100 octane for military purposes, there seems no reason why many of these plants should not continue to operate after the war, and assuming the demand is as great as we anticipate, produce what is now termed grade 100/130 petrol at a cost of about 1s. 6d. per gallon, excluding duties.

We shall continue to look to the military engine as the proving ground for even better fuels, and there is substantial evidence to indicate that we shall not be disappointed, both as regards rich mixture performance for fighter aircraft, and more important for post-war purposes, weak mixture rating for economical cruising in long range airliners.

The introduction of much improved fuels such as Triptane, which in conjunction with the addition of tetra-ethyl-lead, might allow the use of compression ratios as high as 10:1, and could well revolutionise the possible power output and specific fuel consumption attainable with a given size of engine. Thus for military and certain special applications in the civil field, we must encourage still closer collaboration between the petroleum industry and the aero engine and aircraft manufacturers, in order to promote the fullest appreciation of mutual problems, which is absolutely essential for achieving the best results.

Reference should be made here to the use of water injection. Though much work has been carried out with this method of suppressing detonation under rich mixture conditions in America, and some in this country, it would appear that the new fuels with superior rich mixture ratings can supplant water injection for military purposes, and though it is difficult at this stage to visualise the relative merits of dual systems versus improved take-off fuels for civil purposes, it appears that the whole question will be reduced to one of cost. If the airline operator requires a step-up in take-off power for high wing loading machines or for glider towing, he will have to balance cost against simplicity of the installation. Undoubtedly if the fuel with a rich mixture performance in excess of that of normal 100 octane grade can be obtained, for only a fractional increase in price, he will avoid the additional complication of a dual fuel system, but if such fuel is appreciably more expensive, and affords no benefit under weak mixture cruising conditions, then it would pay to go to water injection. It would rather appear that from military aspects we have been so slow in taking advantage of water injection that we have, except in certain instances, missed the opportunities which it would have afforded during the interim period when the equivalent performance fuel could not be made available.

The question of what fuels will be used in the future is naturally to a large extent bound up with problems of carburation. In 1938 the Germans completely abandoned the normal carburettor in favour of direct petrol injection, and a number of reasons have been put forward as affecting their policy on this matter. There is much to be said for departing from the various methods of making the intake air do the job of drawing the required amount of petrol from float chamber fed jets, and adopting precision mechanical devices for accurately metering the required amount of petrol, together with the introduction of this fuel into the air charge exactly where and when it is found most desirable. It is of interest to note here that in the early 'thirties the British Air Ministry appreciated the necessity for looking into the possibilities of timed fuel injection, and the Bristol Company undertook a programme of work on a suitably converted Pegasus engine known as the Draco. Fig. 54 shows a rear view of this power unit. The engine performed entirely satisfactorily, although the actual power output characteristics showed no advance over those obtained with a conventional carburettor. In view of this and the relatively high cost of the injection equipment it was not thought worth pursuing at that time.

587

FIG. 54.
Bristol Draco 9-cyl. air-cooled radial with direct fuel injection, 1933.

So many different forms of petrol injection systems have been tried and are still being developed, notably the S.U. system, the C.A.V. Bosch and other jerk pump types, together with the Bendix-Stromberg equipment developed in America, that it is impossible to deal with the merits of them here, but in connection with direct injection it would appear to have so many advantages that we may see its universal adoption, when engine makers have a little respite after the war to look round and take what is the best of aero engine design features all over the world, and adapt them for the future generation of classic reciprocating engines.

As a logical corollary to the possible universal introduction of timed and metered fuel supply to the engine, we should seriously review the possibilities of using safety fuel, particularly for civil aircraft.

Safety Fuels.

We now come to the question of the fire risk of petrol, and this is a subject which I would like to stress as affecting the future safety of civil aviation. Although we are told to expect great improvements in the layout of petrol systems, and the introduction of a variety of devices to obviate the risk of fire to the utmost in future of civil aircraft, one cannot help feeling extremely concerned about carrying around 80,000 lbs. of highly inflammable fuel, which is what will happen in some of the larger transports of the future already envisaged. There is, in my opinion, too great a tendency to minimise the importance of fire risk on post-war civil aircraft, and one is told that serious conflagrations only occur when there is a sudden crash into a hill or other unseen object in bad weather, and that then, in any case, the people are killed. It is not considered that this is true, and there is good reason to believe that many lives could have been saved in the past, if a high volatility fuel had not been used. Against the fire risk of petrol, it is stated that most fires start from lubricating oil, and that whereas there is little fire risk due to spraying petrol on a hot exhaust pipe, oil will cause a conflagration at 330°C. As far as initiation of the fire is concerned, this may be true, but a fire from oil by itself is much slower in taking hold, and there is not the instantaneous explosion that occurs through petrol being released over a wide surface and thereby evolving a highly combustible or explosive mixture.

After the war we should, therefore, give careful consideration to certain of the low volatility blends generally known as safety fuel; such a type of fuel was proposed many years ago, and some experiments were carried out in France and later in America. A high octane fuel of this type with a flash point of not less than 40°C. will also have a high self-ignition temperature, and a vapour pressure too low to form an explosive mixture with air at ordinary temperatures. From the latest developments it would appear that high octane safety fuels of about 95 to 100 octane rating could be made available in substantial quantities, and although their cost would be, at first, higher than that of 100 octane petrol, if the demand were great enough prices would subsequently drop to values approaching those for equivalent supplies of petrol. Such a fuel would largely eliminate the danger of fire. Again when we think of operating civil aircraft at high altitudes, the problem of vapour lock will be entirely obviated with safety fuels, and from the standpoint of air-cooled engines, a type of safety fuel can be made which has the important advantage of retaining its high anti-detonating characteristics at high intake and cylinder wall temperatures.

Properties.	100/130 Grade Petrol.	Possible High Grade Petrol	Safety Fuel.	Aviation Diesel Fuel.
Specific Gravity ...	.72	.71	.75	.86
Flash Point (closed) ...	−25°C. (or lower)	−25 C. (or lower)	40 C.	80 C.
Calorific Value (nett)...	19,000 B.T.U./lb.	19,000 B.T.U./lb.	19,000 B.T.U./lb.	18,500 B.T.U./lb.
Initial Boiling Point ...	40 C.	40°C.	150°C.	200 C.
Final Boiling Point ...	180°C.	150°C.	100°C.	360°C.
T.E.L. Content ...	5½ c.c.s./I. Gall.	7 c.c.s./I. Gall.	5½ c.c.s./I. Gall.	--
Octane No. (A.S.T.M.)	100	120 (relative)	100	—
Octane No.	—	—	—	55-60
Freezing Point ...	−60°C.	−60°C.	−50°C.	−20°C.
Vapour Pressure (Reid @ 37.80 °C.) ...	7lb. sq. in.	7lb. sq. in.	0.1 lb. sq. in.	0.02 lb. sq. in.

FIG. 55.

Tabulation of the characteristics of aviation fuels.

Fig. 55 shows comparatively the main characteristics of a number of aviation fuels.

Safety fuels cannot be employed with an ordinary carburettor, and entail the application of direct fuel injection, but as it is envisaged that conventional carburettors will be dispensed with as quickly as is reasonable, on anything but the simplest and cheapest aero engines of the future, it is not considered that this is a particularly undesirable feature. It is seriously submitted that the question of safety fuels must receive high priority, and be carefully investigated for post-war civil aircraft.

The alternative to using safety fuels in the reciprocating engine is to develop the aviation Diesel engine. We are all familiar with the way in which the development of the high speed Diesel crept up on the petrol engine until it looked as if the latter, round about 1928-1932, might be hard put to it to maintain its lead, particularly on long range work. Then along came 87 octane fuel, and subsequently 90 and 100, in quantity production, and the aircraft Diesel again took a back seat.

As far as fuel for the aviation Diesel is concerned this would probably be met by the general characteristics given in Fig. 55. One problem in manufacturing such a fuel is the difficulty of obtaining a low freezing point in conjunction with a good octane value.

With present developments on high octane petrols, and the possibilities of still further reduction on fuel consumption of the petrol engine with the adoption of efficient turbo superchargers, it is difficult to predict whether, even in view of its high thermal efficiency, the Diesel engine could give very much lower specific consumptions, but assuming the cost of Diesel oil would always be something of the order of 6d. per gallon less than safety fuel or 100 octane petrol, the reduction in running costs for long hauls of 3,000-4,000 miles must be taken into consideration. In the same way that the Diesel engine for road vehicles has proved its merits for heavy transport work, so might the aviation Diesel be used for long range freight carrying aircraft.

As the Diesel engine has not the rich mixture response characteristics of the petrol engine, it is probable that some form of assisted take-off arrangements such as rockets or towing might have to be resorted to, and such complications, together with the question of fuel distribution to the operating points, may do much to outweigh the potential merits of the Diesel engine and discourage its development. This whole question of alternative prime movers for aircraft propulsion has now become so complex, that we have arrived at a time when engineers should take stock of the situation, and in collaboration with the fuel companies and civil airline operators, decide once and for all whether the compression ignition engine is worth developing for future long range aircraft.

Were it not for the advent of the gas turbine, which promises to provide similar advantages as regards reduced fire risk and low priced fuel, one would recommend the active pursuance of full-scale aviation Diesel engines for special purpose aircraft. Under the circumstances, however, it is felt that development should be proceeded with on high priority, but limited to, single and twin-cylinder units, designed for possible subsequent application to a suitable main engine layout. Now that the sleeve valve engine is well established, the two stroke Diesel using the open ended sleeve offers considerable attraction. With assisted take-off the engines could be designed to cruise economically at something like 80 per cent. of their maximum power, and under these conditions the specific weight in terms of cruising power could be comparable with that of a contemporary 4-stroke petrol engine running on 100 octane fuel.

Lubricating Oils.

Compared with the progress which has been made on fuels over the last 20-30 years, the amount of development work on improved lubricating oils for aero engines has not been very outstanding. Some work has been carried out

on the effects of various additives for alleviating piston ring gumming and providing higher film strengths at elevated temperatures, but whereas in the case of fuels the technique has advanced to a stage whereby a knowledge of the constituents of the material can be used as a reasonably accurate basis for estimating its performance in the engine; with lubricating oils we are as yet only aware that they are composed of a very large number of complex hydrocarbons whose exact identification is beyond the capacity of the petroleum technologists.

Seeing that nearly all the components in an aero engine depend for their satisfactory performance upon adequate lubrication, every effort must be made towards developing better quality lubricating oils. If, however, there is to be any notable improvement for the future, we must establish the closest possible collaboration between the engine manufacturer and the oil companies.

British aero engine development over the last fifteen years has, it is submitted, suffered a handicap through the practice of conducting development work and all type testing of military engines on oil purchased to a Government specification, viz., D.T.D.109, which necessitated that the engine should, so to speak, be designed to run on a variable and indifferent quality of oil. Furthermore, since all that was required of the oil supplier was to meet the specification at the lowest possible price, there was not very much inducement or opportunity for the oil companies to undertake programmes of research, towards the development of high performance lubricating oils. This situation is only slightly altered by the modified D.T.D.472 specification.

As a first step it would appear desirable by a process of extended bench and flight testing to establish, in lieu of a physical specification, the best combination of available crudes and existing refining processes, which would provide the highest possible standard of bulk supply for use all over the world in all aero engines. In addition it would be necessary to meet the demands of the most critical engines with suitable additives, which would also be used without harm in all other engines not necessarily demanding them.

Steady progress in the development of aviation oils must be assumed with such close collaboration as has been indicated, and although some work has been carried out to date, on various film strength additives to reduce piston and ring scuffing tendencies, it is reasonable to expect further improvements. Recent developments on detergents have also shown promise in reducing ring sticking and sludging, but one of the problems has been to find suitable compounds which perform these important functions, without bringing in their wake corrosion troubles or deposits in the cylinders. Meanwhile, the most thorough chemical and physical investigations should be urged, in order to sort out the factors governing the performance of oils in the engine, with a view to establishing certain fundamental criteria, which might subsequently be used as a basis for a reliable specification. Such investigation may also, in the light of what has been accomplished with fuels, permit synthetic production of oils from a wider range of crudes, involving where necessary the re-arrangement of the hydrocarbon groups to meet the requirements of efficient lubrication.

This drive for better oils is absolutely essential, if we are to take advantage of high octane fuels and increased performance per unit swept volume without resulting in ring sticking, seriously restricting bearing loading, or being driven to materials which are difficult to procure or costly to use. In addition it is one of the aero engine manufacturer's most important aims to obtain the longest possible period between overhauls, consistent with the utmost reliability and reasonable engine size and weight. There is much scope for the oil companies to assist on this score, and there is no doubt that given full opportunities they will provide the necessary co-operation.

(To be continued).

CORRESPONDENCE.

To the Editor of the JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY.

DEAR SIR,—I should like to draw your attention to one or two statements in two recent papers on rocket propulsion that have appeared in the Journal, which I think may be erroneous.

In addition to the results in "The Development of Jet and Rocket Propulsion," by J. Stemmer, corrected by Mr. Coleridge, in the June issue of the Journal, I would like to mention the following:

(1) The expression $V_2 = \binom{2}{n} c$ on p. 400, should be $V_2 = \frac{c}{2} + \frac{c}{n}$

and the expression $V_k = \binom{k}{n} c$ should be $V_k = \frac{c}{2} + \left\{ \frac{(k-1)}{n} \right\} c$

This is borne out by the expression further down the page $V_n = V_0 + \binom{n}{2} c$.

(2) On p. 410 the discharge velocity should be 2,000 m/sec., and the expression for V_x should be $V_x = \left(\frac{560}{100} \right) \times 2{,}000 = 11{,}200$ m/sec.

(3) On page 411, the expression

$$M = \left(\frac{30}{2{,}000} \right) M \text{ means that } \left(\frac{1}{66\frac{2}{3}} \right) M \text{ and not } \left(\frac{1}{150} \right) M$$

must escape per second, which shows that the rate of projection is the same as if $\left(\frac{1}{100} \right) M$ were projected 1.5 times a second (as on p. 140).

(4) On p. 413 the expression at the top of the page should be

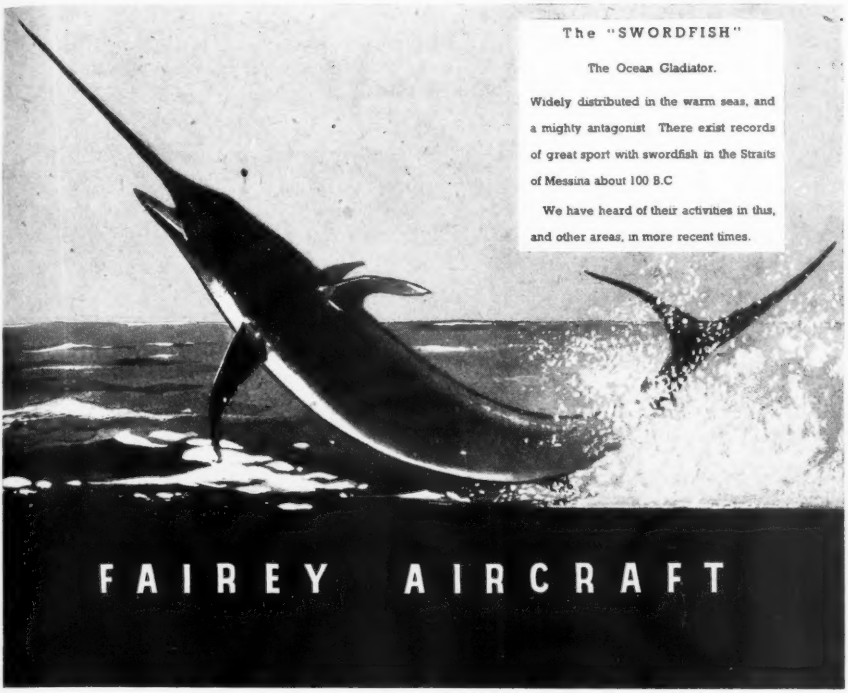
$$M = M_0 2 \cdot 7^2 \left(\frac{2{,}000}{3{,}000} \right) = 2M_0$$

i.e., the initial mass M is twice the final residual mass M_0, and consequently the propellant to be carried must be equal to (and not twice, as stated) the empty weight of the aircraft.

On p. 60 of the March Journal—in the paper, "Rocket-Wing-Bomb and Rocket Torpedo," by Krzywoblocki—expression (18) should be $\eta = R v / L_g = 0$. Incidentally, why work out this expression? In every case, surely, no velocity—zero efficiency!

Yours faithfully,

S. W. GREENWOOD, Stud. R.Ae.S.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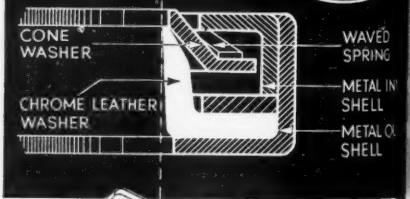

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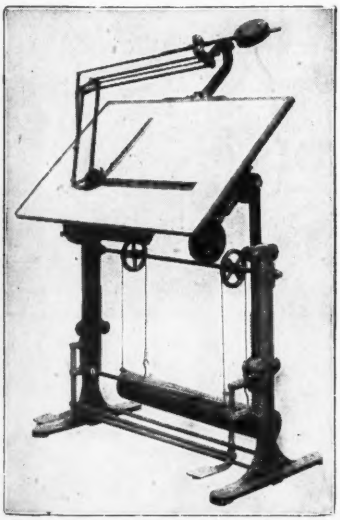

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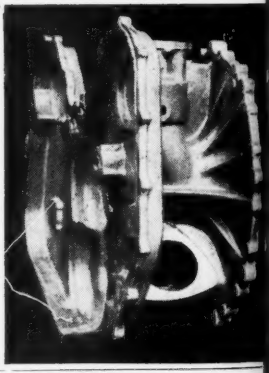

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